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STABILIZATION OF SEWAGE SOLIDS BY THE CHANNEL AERATION PROCESS

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June 1973

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The use of an oxidation ditch for treatment of domestic sewage sludges by aerobic digestion was found to be superior to anaerobic digestion. Maximum reductions of 64.7% for volatile solids and 67.8% for COD were achieved. Low temperatures inhibit the process such that below temperatures of 55°F neither of these reductions exceeded 45%. At moderate temperatures the DO content of the mixed liquor appears to be the factor limiting COD and volatile solids reductions. When the DO content exceeds 1.5 ppm the reductions of COD and volatile solids reached their maximum values, however, nitrate and phosphate concentrations in the mixed liquor increased to values of 30 ppm and 115 ppm respectively. The dewatering characteristics of the digested sludge were found to be no better than those of raw sludge.

Evidence also indicates that this process is better suited to continuous rather than semi-continuous operation. The process also requires close control of operating conditions. Operating costs were found to be $36.50 per ton of solids treated.

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ABSTRACT

The use of an oxidation ditch for treatment of domestic sewage sludges by aerobic digestion was found to be superior to anaerobic digestion. Maximum reductions of 64.7% for volatile solids and 67.8% for COD were achieved. Low temperatures inhibit the process such that below temperatures of 55°F neither of these reductions exceeded 45%. At moderate temperatures the DO content of the mixed liquor appears to be the factor limiting COD and volatile solids reductions. When the DO content exceeds 1.5 ppm the reductions of COD and volatile solids reached their maximum values, however, nitrate and phosphate concentrations in the mixed liquor increased to values of 30 ppm and 115 ppm respectively. The dewatering characteristics of the digested sludge were found to be no better than those of raw sludge.

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CONTENTS

Section		Page
I	Conclusions	1
II	Recommendations	3
III	Introduction	5
	Background	5
	Literature Review	5
	The Project	7
IV	Plant and Equipment Description	9
V	Experimental Phase	15
	Analytical Procedures	16
	Special Studies	20
VI	Discussion	23
	Mixing and Flow Effects	23
	Oxygenation Performance	27
	Temperature Effects	27
	Process Efficiency	30
	Sludge Dewatering Characteristics	38
	Analysis of Costs	40
	Comparison of Aerobic and Anaerobic Digesters	42
VII	Acknowledgements	45
VIII	References	47
IX	Glossary	49
X	Appendices	51
	Appendix A - Data for Ditch 10	51
	Appendix B - Data for Ditch 11	67

CONTENTS (cont.)

Appendix C - Data for Ditch 12	71
Appendix D - In-laboratory Studies	75
Experimental	75
Discussion	77
References	89
Glossary	90

FIGURES

No.		Page
1	Digester Layout	9
2	Cross Section of Channel	10
3	Floating Aerators in Operation	11
4	Diagram of Propellor Type Flow Inducer	12
5	Cage Rotor in Operation	13
6	Automatic Sludge Sampler	16
7	Mixed Liquor Sampler	17
8	Apparatus for Dewatering Studies	21
9	Areas of Settling in the Aerobic Digester	23
10	Sampling Locations	24
11	Extent of Scum Mat	25
12	Accumulation of Volatile Solids in Ditch 10	33
13	Volatile Solids Reduction Versus Day of Ditch (Ditch 10)	33
14	Variations in Total Bacteria Population Within a One-Day Time Interval	34
Appendix D		
1	In-lab Digester and Recorder	75

TABLES

No.		Page
1	Frequency of Analysis of the Various Samples	19
2	Total Residue of Mixed Liquor at Various Sampling Sites	24
3	Chemical Oxygen Demand of Supernatant Liquor at Various Sampling Sites	25
4	Total Residue of Mixed Liquor at Various Depths at Site 3	25
5	Chemical Oxygen Demand of Mixed Liquor of Various Sampling Sites	26
6	Total Residue and COD at Various Depths at Sampling Site Number 2	26
7	Dissolved Oxygen in Mixed Liquor	28
8	Comparison of the Outside Air Temperature and the Temperature of the Mixed Liquor	29
9	Process Efficiencies of Ditch 10, 11 and 12	30
10	Daily DO limits of Ditch 10 and Corresponding Concentrations of Nitrate and Phosphate	31
11	Bacterial Populations of Ditch 10	35
12	Total Bacterial Populations in Ditch 11	37
13	Dewatering Characteristics of Digested Sludge	39
14	Dewatering Characteristics of Raw Sludge	40
15	Design and Construction Costs	41
16	Operating Costs for Ditch 10	42
17	Data from Anaerobic Digester	43
18	Comparison of the Overflows of an Aerobic Digester and an Anaerobic Digester	44
19	Data for Ditch 10	51
20	Chemical Oxygen Demand of Supernatant Withdrawn from Ditch 10	54

TABLES (cont.)

No.		Page
21	Data for Ditch 10 - Solids	55
22	Data for Ditch 10 - COD and Phosphorus	59
23	Data for Ditch 10 - Nitrogen	63
24	Data for Ditch 11	67
25	Data for Ditch 11 - Solids	68
26	Data for Ditch 11 - COD and Phosphorus	69
27	Data for Ditch 11 - Nitrogen	70
28	Data for Ditch 12	71
29	Data for Ditch 12 - Solids	72
30	Data for Ditch 12 - COD and Phosphorus	73
31	Data for Ditch 12 - Nitrogen	74
Appendix D		
1	Daily Dissolved Oxygen Levels	78
2	Daily Total Bacterial Population Counts	79
3	Unit 2 Time Study Dissolved Oxygen Data (unsterilized raw sludge additions)	80
4	Unit 2 Time Study Dissolved Oxygen Data (sterilized raw sludge additions)	80
5	Unit 1 Time Study Dissolved Oxygen Data (unsterilized raw sludge additions)	81
6	Unit 1 Time Study Population Change	84
7	Unit 2 Time Study Population Change	84
8	Unit 3 Time Study Population Change	85
9	Reduction in Volatile Solids	86
10	Percent Reduction of Volatile Solids	87

SECTION I

CONCLUSIONS

1. Propeller type flow inducers, unless equipped with large propellers and large motors and turning at high rpm are not suitable for propulsion of the liquid in an oxidation channel.

2. Floating surface aerators alone are not a suitable means for providing aeration of liquid in a closed channel. Flow in the channel, especially on the surface, is retarded when these units are in operation.

3. The temperature of an oxidation ditch, used for sludge treatment only, is greatly influenced by ambient air temperature. This is due to the low turnover rate of the digester contents. Heat losses during winter operation may be too great to allow maintenance of the temperature of digester contents at a level necessary for efficient operation.

4. Low temperature of the digester contents reduces the biological activity as evidenced by lower reductions in COD and volatile solids. Digester contents should be maintained at no less than 55°F, preferably near 70°F.

5. Dissolved oxygen content of the mixed liquor should consistently exceed 1.5 ppm to realize near optimum reductions of COD and volatile solids.

6. During periods of high DO content in the mixed liquor, in excess of 2.0 ppm, when reductions of COD and volatile solids are greatest, the nitrate and phosphate content of the liquid portion of the mixed liquor is also greatest.

7. Volatile solids reductions of up to 64.7% were obtained up to a total solids content of 1.7%. Above this level, volatile solids increased quite rapidly indicating reduced process efficiency.

8. Maximum reductions of volatile solids, COD and nitrogen obtained by an aerobic digester of this type were 65%, 68% and 55%, respectively.

9. Bacterial populations fluctuate widely in a semi-continuous operation as they undergo an extensive starvation period between sludge additions.

10. The effluent from the channel aerobic digester was compared with the effluent of an anaerobic digester. The COD of the effluent from the anaerobic digester was found to be 18 times that of the effluent from the aerobic digester. The organic nitrogen and ammonia contents of the anaerobic digester effluent were greater by factors of 5 and 83 respectively. This represents the increased load placed on the remainder of the plant by the anaerobic digester.

11. The channel aerobic digestion process requires constant manual or automatic control as the process is very sensitive to temperature changes and the DO content of the mixed liquor.

SECTION II

RECOMMENDATIONS

1. Propellor type flow inducers and floating aerators are not suited for use in an oxidation ditch.

2. The oxidation ditch itself is not suitable for sludge treatment in the Northern United States as the low outdoor temperatures result in low temperatures of the digester contents. Contents of the digester must be heated to attain efficient operation.

3. Use of aerobic digestion for sludge must be accompanied by tertiary treatment for removal of nitrate and phosphate from the digester supernatant if the digester supernatant is to be recycled or discharged.

4. To achieve good reductions of volatile residue and COD, the DO in the mixed liquor must be maintained in excess of 1.5 ppm. Above 2.0 ppm the degree of nitrification is undesirably high.

5. Care must be exercised in the design of an aerobic digester. The process should be automated to the highest degree possible to reduce operating costs and eliminate operator error.

6. Plants utilizing aerobic digestion of sludges should be designed as a continuous operation. The bacterial population of an aerobic digester operated on a batch basis shows wide fluctuations suggesting that higher efficiencies could be attained with continuous, or nearly continuous, addition of sludge.

SECTION III

INTRODUCTION

Background

This investigation was designed to test the workability and effectiveness of an aerobic process for the stabilization of sewage solids using an oxidation ditch. While such a process has proven to be very efficient for the treatment of the liquid sewage it has not been used exclusively for the stabilization of the sewage solids.

The most commonly used method of treating sewage for smaller communities employs a trickling filter for the treatment of the liquid and an anaerobic digester for the treatment of the sewage solids which accumulate in the primary and final settling tanks. The digester is usually large enough to retain the solids for approximately 70 days, and during the decay of solids in this digester most of the carbon is released as carbon dioxide or methane, while the nitrogen and phosphorus are released as soluble compounds in the supernatant liquor. This supernatant liquor is generally returned to the incoming raw sewage for subsequent retreatment in the plant. Such treatment plants have been generally considered to be satisfactory in the removal of organic matter and, in particular, for the lowering of the biochemical oxygen demand (BOD) and have therefore been looked upon as satisfactory for the treatment of domestic sewage.

In recent years, however, such treatment facilities have been found to be inefficient in the removal of plant nutrients (i.e., nitrogen and phosphorus compounds) resulting in the growth of unsightly and undesirable rooted aquatic plants and algae in the surface waters receiving discharges of treated wastewater effluent.[1,2,3,4,5]

Thus, it becomes apparent that the successful treatment of sewage must involve not only the removal of the organic matter, but also a large portion of the nitrates and phosphates. Because of this necessity the anaerobic digester may no longer represent a desirable or satisfactory unit in the treatment process. Usually the nitrogen and phosphorus that are released during the anaerobic decomposition of the organic matter are returned to the raw sewage and most will eventually appear in the final effluent. It is obvious that it would be better to remove the solids from the system completely and not allow the nutrients they contain to be reintroduced as soluble components of the effluent. Therefore, when the sewage solids are removed from the liquids it would be better if they were not treated in a manner that would allow the plant nutrients (nitrates and phosphates specifically) to be released.

Literature Review

Although aerobic digestion of sewage sludges is not commonly practiced,

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a number of cities are using it to treat domestic sewage sludges. Aerobic digesters are generally large open tanks in which the contents are aerated by means of compressed air introduced through diffusers located at or near the bottom of the tanks. Volatile solids reductions equivalent to those achieved by anerobic digestion can be obtained. The major disadvantage of aerobic digestion is the high power cost.[6] The power cost for compression of air is high. This is primarily due to the fact that only 20% of the atmosphere is oxygen. Therefore, the majority of the gases compressed are not functional during the aeration process. With cage rotor system there is no power expended for the compression of air and the economy thus afforded may make the aerobic process a workable one that could find wide application.

In many of the treatment plants that are using the aerobic process of sludge stabilization it has been presumed that the solids could be stabilized to the stage where they are almost completely oxidized. Frequently, in an attempt to completely oxidize the solids, there is a tendency to build up an excess of dissolved oxygen (DO). It has been shown that an excess of DO leads to an increase in the amount of dissolved nitrate in the mixed liquor.[7] The aerobic digester, for this investigation, was designed with equipment capable of controlling the DO content of the mixed liquor.

Studies have been performed to determine the amount of aeration needed to stabilize the solids, and yet keep it to some minimum level so as not to produce an excessive amount of nitrates.[8] In the studies by Irgens it was observed that when the level of dissolved oxygen was properly controlled it was possible to produce an effluent from the digester with very low BOD and only trace amount of dissolved nitrogen and phosphorus.[9] They found that excessive aeration generated nitrates which remained in the supernatant liquor and subsequently increased the nitrogen content of the effluent from the digester.

While most microorganisms are more tolerant, for longer periods of time, to relatively low temperatures compared to high ones, there is tremendous diversity among microorganisms concerning their response to temperature. Based on their response they have been divided into three groups; thermophiles, mesophiles and psychrophiles. Although there has been some difficulty in defining the temperature optima for these groups it is generally agreed that mesophiles grow best between 20°C and 37°C and thermophiles grow best at temperatures about 40°C.[10] Microbiologists have had a more difficult time agreeing upon a precise definition for "psychrophiles". At one time it was proposed that psychrophiles be defined as the formation of colonies, on solid media, visible to the unaided eye.

Psychrophilic organisms grow at temperatures as low as -10°C, but their optimum growth temperatures still lie in the range of 20°C to 40°C. Ingraham and Stokes added that psychrophilic bacteria with an optimum growth temperature below 20°C have rarely been found.[12] This suggests that even though psychrophilic bacteria are able to grow at low temperatures their

growth, like that of mesophiles and thermophiles, is retarded at temperatures below 20°C. Various investigators have reported a retardation of microbial activity as the temperature drops below 15°C.[13,14] Grube and Murphy reported an inhibition of nitrate formation in the contents of an oxidation ditch in College, Alaska, at temperatures below 12°C.[15] This indirectly supports the results of Somers who reported the inhibition of nitrifying organisms at temperatures below 12°C.[16] Schroepfer, et al observed that the efficiency of trickling filters, as determined by percent of BOD removal, was reduced as the ambient temperature and, consequently, the temperature of the sewage, was lowered.[17] Keefer reported that the BOD removal increased from about 84.5% at a sewage temperature of 53°F to 91.5% at 70°F.[18] These data were based on records over a 20-year period at a treatment facility with a flow of 18 to 22 million gallons per day.

The Project

The city of River Falls, Wisconsin, has a relatively new sewage treatment plant. It is a trickling filter system consisting of primary settling tanks, a trickling filter, final settling tanks and chlorination chamber. Initially the city disposed of the solids, removed from the settling tanks, by pumping them into a sludge holding tank. The raw sludge was chlorinated as it was pumped into the holding tank, held for a few days and then discharged directly onto sand beds for drying. Once dried, the sludge was worked into the sand by a tractor and disc. This means of sludge disposal worked well for a few years. However, after a period of time the sludge no longer dewatered promptly after being discharged. This was the result of a residue of hygroscopic organic matter from the solid wastes which had accumulated to the point where the water content of the sludge could no longer percolate freely through the sandy soil. The importance of prompt and complete removal of dried sludge from the beds has been reported elsewhere. Bowers reported that the time necessary to remove all dried sludge from the drying beds was time well spent.[19] Any dried sludge that remains and is worked into the sand and will eventually seal the beds. This did occur at the River Falls treatment plant, and the end result was long-standing pools of solutions of high organic content, which led to anaerobic decomposition. The noxious gases released as a result caused a severe odor problem in the city of River Falls.

The development of the aeration channel method of treating biodegradable sewage appeared to offer a solution to this problem. This method has been used in a variety of locations for treating domestic sewage. The solids removed from the channel following digestion are quite stable and resistant to further biodegradation.

Dr. H.O. Halvorson, visiting some of these treatment plants in Europe, observed that not only were they efficient in lowering the BOD, but it also appeared that the method might represent a solution for the removal of the soluble plant nutrients as well. The effluent coming from these plants contained smaller amounts of nitrogen and phosphorus than was generally found in the effluent of the waste treatment plants employing

an anaerobic digester. In an attempt to confirm these observations, laboratory experiments were conducted using sludge from the primary settling tanks from the city of Urbana, Illinois.[9] The results of this study suggested that an aerobic process could effectively stabilize the solids recovered from domestic sewage. Furthermore, it was observed that during the stabilization of these solids a good deal of the organic matter was consumed by the microorganisms growing in the suspended flock releasing carbon dioxide and water. Approximately one-third of the nitrogen that was present in these solids was lost to the air as free nitrogen gas. The balance of the nitrogen was assimilated by the microorganisms. Similarly, a large portion of the phosphorus was assimilated by the microorganisms resulting in a supernatant liquid that proved to be clear and free from BOD and contained less than 10 ppm of phosphate and nitrate.

In an attempt to correct the air pollution and sludge disposal problems financial aid was sought. Federal assistance, in the form of a Research and Development grant, was made jointly to the city of River Falls and the University of Wisconsin-River Falls, River Falls, Wisconsin. The funds enabled the community to construct an oxidation ditch in an attempt to solve the sludge disposal and odor problems. The funds also provided financial support for the university to conduct research on the effectiveness of the oxidation ditch as a sludge stabilization unit.

The oxidation channel was so constructed that there was considerable flexibility in the methods of operation, so that it was possible to determine the limits of the important variables that needed to be controlled for efficient operation of the process. In the original proposal these variables were; 1) the level of dissolved oxygen, 2) the limits in the level of total solids, and 3) the frequency of removal of solids from the digester. An additional phase, which was not an integral part of the original proposal, was added sometime after the study began. This phase was concerned with the influence of the temperature of the ditch contents on the physiological activities of the microorganisms. During the first winter months of operation it became evident that the oxidation ditch was not adequately insulated and that the ambient temperature was very influential on the temperature of the digester contents and consequently on activity of microorganisms within the channel.

The propulsion and aeration systems that were put into operation were different than those described in the original proposal. In place of cage rotors, which represent both the propulsion and aeration systems, separate propulsion and aeration systems were installed. Separate and individual control of the flow inducers and aerators provided greater flexibility for research aspects of the project.

SECTION IV

PLANT AND EQUIPMENT DESCRIPTION

The waste water treatment facility at River Falls, Wisconsin, utilizes a trickling filter as a secondary phase of treatment. The sewage treated at this plant consists, almost exclusively, of domestic waste water. The sanitary sewer system is separate from the storm sewers. During the academic year (September to June), there are approximately 10,000 persons tributary to the system. During the summer months this population is reduced to approximately 8,000 persons.

The sludge is comprised of the solids which collect in the primary and secondary settling tanks. The sludge is removed from the settling tanks by means of pumps and the volume is metered as it is pumped to the digester.

The digester was constructed in the shape of an oval with a circumference of 400 feet (Figure 1).

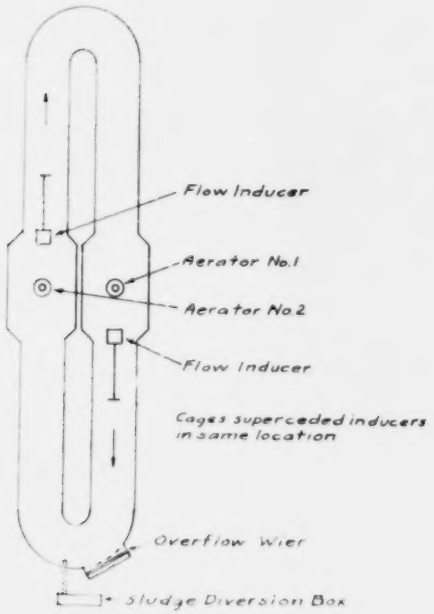

Figure 1. Digester Layout

The floor of the channel is 8 feet 6 inches wide. The walls have a 1:1 bevel to a height of 3 feet 9 inches making the width at this point 16 feet. Upward from the 3 feet 9 inches level the walls are perpendicular to the floor (Figure 2). Two sections of the channel were constructed 30 feet long by 24 feet wide, to allow operating space for the surface aerators. The entire channel, with the exception of the wide areas, is covered by board and tar paper. This covering is anchored to the top of the channel walls leaving a clearance of seven feet from the channel floor. A wood frame enclosure, measuring 40 feet long by 50 feet wide was constructed over the wide areas of the channel. The walls of the enclosure rise 17 feet 4 inches above the digester floor. This area houses the aeration and propulsion equipment. Sets of double doors were installed at diagonally opposed corners of this aeration room to provide access to the equipment.

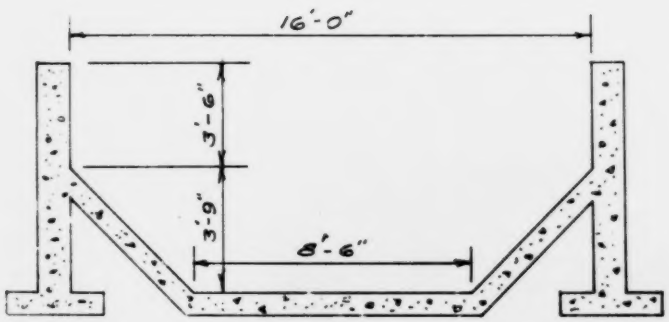

Figure 2. Cross Section of Channel

The depth of the digester contents is regulated by means of a variable overflow wier installed in one end of the channel. The overflow wier is a large metal pipe, 16 inches in diameter and 15 feet long, suspended parallel to the liquid level by metal flanges imbedded in the concrete wall. The pipe has a two inch slot running lengthwise and by rotating the pipe the slot is turned to vary the level of the digester contents. The wier was not metered and the volume of supernatant or mixed liquor removed was determined by measuring the level of the digester contents

before and after such removal. The minimum and maximum depths of mixed liquor in the digester are 3 feet 9 inches and 5 feet, respectively. These depths correspond to volumes of 167,400 gallons and 228,600 gallons, respectively.

A wier house was constructed to enclose the overflow wier and sludge diversion box. The raw sludge is pumped from the collection basins of the settling tanks into a cement diversion box measuring 3 feet deep by 2 1/2 feet wide and 12 feet long. After entering the diversion box, the sludge passes through a one inch bar screen before entering the digester. The solids removed by this bar screen are hauled to a landfill. A continuous sampler and sludge volume metering equipment were located here.

The aeration equipment consisted of two floating aerators manufactured by Richards of Rockford, Rockford, Illinois. Each aerator was powered by a 15 hp electric motor and had an aeration capacity of not less than 3.0 pounds of dissolved oxygen per rated hp per hour. The floating aerators, moored in the wide portion of the channel, drew the mixed liquor from near the bottom of the digester and sprayed it through the air. Figure 3 shows a floating aerator in operation. The aeration equipment was controlled by a Delta Scientific Corporation Model 322-P automatic dissolved oxygen analyzer controller.

Figure 3. Floating Aerators in Operation

This equipment receives the signal from the oxygen diffusion electrode (probe) which is dependent on the DO content of liquid in which it is immersed. If the signal received is outside of the pre-set DO range, a relay is activated and the aeration equipment started up or shut down as required.

To maintain solids in suspension in the channel, it was necessary to provide mechanical propulsion equipment. The original equipment consisted of a pair of flow inducers manufactured by Industrial Kinetics, Inc. of St. Paul, Minnesota. Each inducer consisted of a 30 inch screw propeller on a shaft driven by a 5 hp motor. (Figure 4). One of these inducers was mounted on each side of the digester immediately downstream from the floating aerators. The flow inducers were mounted on pivots to allow the propellers to be raised and cleaned of matted hair and rags.

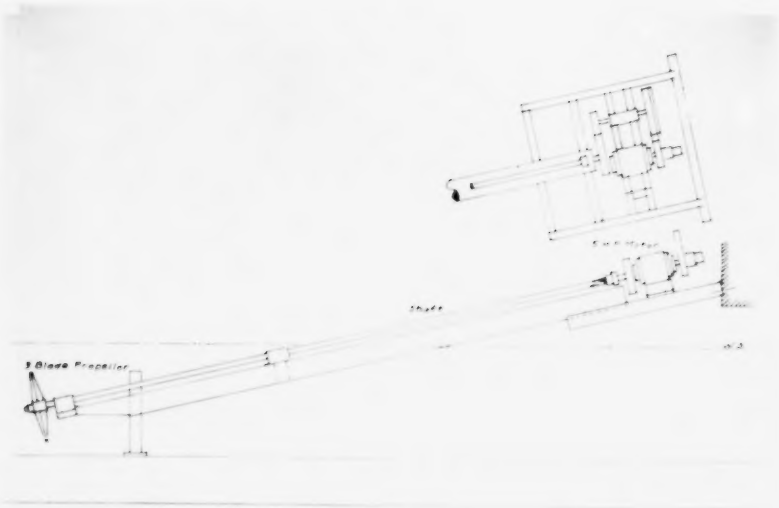

Figure 4. Diagram of Propellor Type Flow Inducer

When operating simultaneously, the propeller type hydraulic flow inducers were to propel the mixed liquor around the digester at a velocity of 1 to 1 1/2 feet per second. This specification was not met and these inducers were replaced by a pair of cage rotors.

The cage rotors (Figure 5) were acquired from Cherne Industrial, Inc. of Hopkins, Minnesota. Each of the cage rotors is 7 feet long and 30 inches in diameter with blades which have a maximum immersion depth of 6 inches into the digester contents. The rotor blades are solid, not perforated, so that a significant fraction of the liquid aerated is carried over the top of the rotor. To prevent this liquid from striking the surface of the channel, thus hindering the surface flow, a splash plate was mounted just behind the rotor to intercept it.

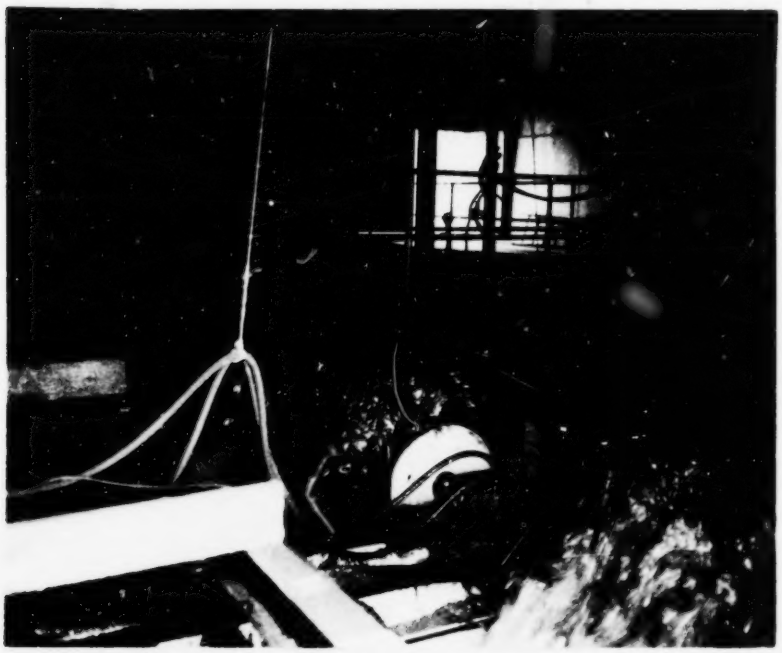

Figure 5. Cage Rotor in Operation

Each of the rotors is driven by a 7.5 hp electric motor. The motors were connected to the rotors through a gear reduction system such that the cage rotors turned at a speed of 66 rpm.

SECTION V

EXPERIMENTAL PHASE

The variables believed to be of greatest influence on the efficiency of stabilizing sewage solids by the extended aeration process are the temperature of the digester contents, the dissolved oxygen level, the level of solids accumulated in the digester and the microbial population. The circulation velocity in the channel is not considered an important process variable as it is apparent that there is some minimum velocity necessary to keep solids in suspension and that any velocity over and above this minimum simply represents unnecessary expenditure of power. It has been documented that a velocity of 1.0-1.5 feet per second in an oxidation ditch is adequate to keep sewage solids in suspension.[20,21] This would ensure the digester contents are well mixed, a condition which must exist if maximum efficiency is to be realized.

To determine the effect of these variables on the process efficiency, experiments were designed to answer the following questions.

1. To what extent does the ambient air temperature affect the temperature of the digester contents and consequently the efficiency of the process?

2. At what total solids level can the digester be operated and still produce satisfactory reduction in volatile residue, COD and plant nutrients?

3. What is the process efficiency (at various levels of solids) as defined by the percent reduction of COD, volatile residue and nitrogen?

4. What relationship exists between the level of dissolved oxygen carried in the aerobic digester and the nitrate concentration in the supernatant liquor of the digester?

Additional experiments were designed to answer the following supplementary questions.

1. How does the effluent from an extended aeration digester compare with the overflow from an anaerobic digester with respect to COD and plant nutrients?

2. What is the maximum level at which solids may be maintained in the digester before the aeration system proves inadequate or solids cannot be maintained in suspension?

3. What are the dewatering characteristics of the digested sludge as compared to raw sludge?

4. What is the power cost in terms of kilowatt hours per ton of waste treated, as determined by total solids?

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Analytical Procedures

The process studied in this project is a semi-continuous process as no provision was made for continuous addition of raw sludge to the digester. Raw sludge from the primary settling tank and any solids collected in the final settling tank were pumped to the digester twice daily at approximately 9:00 A.M. and 9:00 P.M. The volume of sludge was metered as it was pumped to a diversion box where an automatic sampler was located (Figure 6). A composite sample was prepared from the two daily pumpings according to the ratio of volumes pumped at each time. The sample was stored at 36-40°F until the laboratory analyses could be performed (approximately 12 hours).

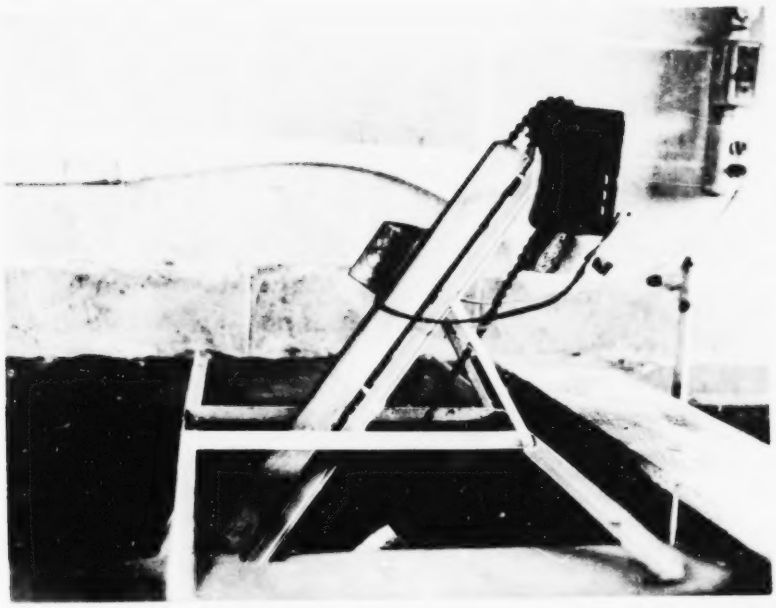

Figure 6. Automatic Sludge Sampler

A representative sample of the digester contents was obtained by the following sampling technique. A large opening in the top of the sampler (Figure 7) was stoppered and the sampler was lowered into the digester. After the sampler reached the desired depth, the stopper was removed, allowing the sampler to fill with mixed liquor. Several studies were conducted to determine if the samples obtained in this manner were representative of the digester contents. Samples were taken at various locations and depths in the digester. The samples were shown to be

represenative of the digester contents by these investigations.

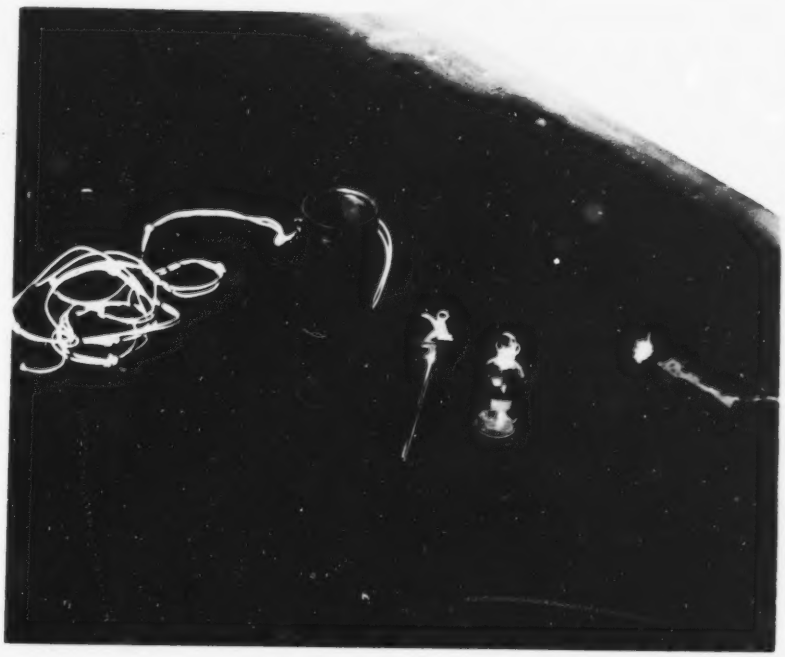

Figure 7. Mixed Liquor Sampler

A permanent sampling site was chosen and to minimize possible variations in the sample, the aeration and propulsion equipment were in operation at the time any sample was withdrawn from the digester. The sample of digester contents was removed daily, shortly before sludge was added to the digester at 9:00 A.M. The supernatant liquor sample was obtained by allowing the mixed liquor sample to stand until solids had settled sufficiently to allow clear supernatant to be withdrawn.

Each day the plant operators recorded the temperature, depth of mixed liquor in the digester and the volume of raw sludge pumped. The minimum and maximum ambient air temperatures were also recorded daily and compared with the temperature of the digester in order to determine the effect of outside temperature on the efficiency of the process. Approximately 6,000 gallons of sludge was added to the digester daily. This made necessary the periodic removal of clear supernatant. Hence, at least once each week the aeration and propulsion equipment were shut down to allow settling of the solids. After the solids had settled sufficiently, the overflow wier was rotated and approximately 45,000 gallons of clear supernatant were removed from the digester. Analyses

were performed to determine the quality of the supernatant liquor removed.

The principle reference used for the analytical work performed was Standard Methods for the Examination of Water and Waste Water, 12th Edition (hereafter referred to as Standard Methods).[22] This reference provided many of the procedures and some of the background for the analyses conducted. These analyses included total residue, total volatile residue, COD, ammonia, nitrate, organic nitrogen and phosphate. Additional tests run less frequently included 5 day BOD, total phosphorus, pH, dewatering and bacterial studies.

The analysis for ammonia and organic nitrogen concentrations was the phenol-hypochlorite method developed by Russell (1944)[23] and McKenzie and Wallace (1954).[24] This method was adopted because of its greater simplicity in comparison to the methods described in Standard Methods for the Examination of Water and Waste Water, 12th ed. Results were found to be comparable.

The total phosphorus method sanctioned by the Department of Natural Resources of the State of Wisconsin[25] was chosen because of the physical inability to filter mixed liquor or raw sludge samples in quantities large enough to perform the phosphate analysis in Standard Methods. The raw sludge or mixed liquor sample was diluted, if necessary, and 25.0 ml were placed in a phosphate free evaporation dish. To this, 1.0 ml of a 10% solution of $Mg(NO_3)_2$ was added and the sample was evaporated to dryness. The sample was then ignited over a burner for about 5 minutes until only a white ash remained. After cooling, 2.0 ml of a solution containing 150 g/l of ammonium molybdate ($(NH_4)_6Mo_7O_{24}\cdot 4HOH$) were added, wetting all of the ash in the dish. The sample was transferred from the porcelain dish to a 125 ml erlenmeyer flask and diluted to 50 ml. The remainder of the procedure was identical to that for the development of color with amino naphthol sulfonic acid in the determination of orthophosphate as found in Standard Methods. The blank for the total phosphorus procedure is prepared in the same manner as the sample except 2.0 ml of the strong acid solution specified in the orthophosphate method are added instead of 2.0 ml of ammonium molybdate to wet the ash after ignition.

Table 1 shows the frequency of each analysis for the samples collected. Determinations of the COD, total residue and total volatile residue present in the raw sludge were conducted five times per week. The organic nitrogen content of the raw sludge was determined three times per week.

Table 1. Frequency of Analysis of the Various Samples (number of times per week)

	COD	NO_3^-	NH_3	Organic N_2	$PO_4^=$	Volatile Residue
Digester						
Supernatant liquor	3	2	2	2	2	-
Mixed liquor	3	-	-	2	-	3
Raw sludge	5	-	3	3	-	5

A sample of the mixed liquor was analyzed three times per week for COD, total residue, and total volatile residue. This sample was analyzed twice weekly for organic nitrogen. It was assumed that any nitrate or ammonia present in the digester was dissolved in the supernatant liquor, eliminating the need to analyze for these in the mixed liquor sample. The supernatant liquor sample was analyzed three times per week for COD and twice weedly for organic nitrogen, ammonia, nitrate and phosphate content.

The various analyses were performed during periods of plant operation at various temperatures and the reduction of COD, volatile residue and nitrogen were calculated. The efficiency of the process was defined as the percent reduction of volatile residue, COD, and nitrogen during a given period of plant operation. By analyzing the sludge added to the digester, the mixed liquor in the digester and the effluent withdrawn from the digester, information was obtained to calculate the percent reductions. The mixed liquor was analyzed for COD, volatile residue and nitrogen on the first day of the test period to obtain the pounds of these materials present initially (P_i). The raw sludge was analyzed to determine the pounds added (P_a). On days when the sludge was not analyzed, an average of the data from the previous week's analyses was used to determine the amount of COD, volatile residue and nitrogen added. The effluent from the digester was analyzed to determine the quantity of any substance withdrawn (P_r). On the final day of the test period, the mixed liquor was analyzed to determine the pounds of COD, volatile residue and nitrogen remaining in the digester (P_f).

$$\text{Percent Reduction} = \frac{P_i + P_a - P_r - P_f}{P_i + P_a - P_r} \times 100$$

This equation was used to calculate the percent reduction of the parameter under consideration. The assumption was made that any decrease in the weight of COD, volatile residue or nitrogen , as calculated by the numerator in this equation, was due to decomposition by the aerobic process.

The oxygen dissolved in the mixed liquor was also considered an important variable of the process. The dissolved oxygen (DO) in the digester was measured by a DO monitor which received a signal from an oxygen diffusion electrode placed in the channel. The monitor had variable limits and operated a relay which switched the floating aerators on or off, depending on the DO concentration in the digester. The digester contents were aerated in the two widened portions of the channel where the floating aerators were located. By measuring the DO in the mixed liquor moving into each aerator, it was possible to determine if the DO was depleted in moving one half of the distance around the digester. The signal from the DO monitor which was permanently mounted in the plant control room was connected to a strip chart recorder which provided a daily record of the DO in the mixed liquor. The DO of the various mixed liquor samples was determined using a Weston and Stack, Inc. Model 300B portable DO meter. The portable DO meter was standardized daily using the Winkler method for the determination of DO. This portable meter also served as a secondary standard for the meter which was permanently mounted at the plant.

As it was obvious that solids must be kept in suspension during operation of the digester, the velocity flow profile of the channel contents was determined. The necessary measurements were made initially with a Gurley Meter. When the total solids content of the digester reached 5000 ppm, this device became unsuitable, as the solids clogged the moving parts. After the solids content reached approximately 0.5% the rate of movement of the channel contents was determined in the following manner. A longitudinal distance of 25 feet was measured off in the wide portion of the channel. The time necessary for a floating object to traverse this distance was measured with a stopwatch. The rate of movement of the object was then calculated. This rate was taken to equal to the rate of movement of the channel contents.

It was noted that shortly after sludge was pumped to the digester, the DO dropped to zero ppm on the strip chart and remained at this point for a number of hours. A bench scale digester was used to study this phenomenon of shock loading (Appendix D).

Special Studies

Experiments other than those mentioned above, were devised to study the microbial life in the digester. The bacterial population was followed at two hour intervals after raw sludge was added to the channel to determine how the addition of sludge affects the microbial population. A mixed liquor sample was removed from the digester before sludge was added and dilution pour plates were made according to the standard plate count method to determine the bacterial population. After sludge was pumped, the digester was sampled at two hour intervals and dilution pour plates were again made. The pour plates were incubated for 24 hours at 35°C and a total colony count was made. The resulting populations were plotted against time to resolve how the population varied with respect to feeding time.

Arrangements were made to compare the overflow from the anaerobic digester at the Waste Treatment Plant in Hudson, Wisconsin, with the effluent from the aerobic digester. The purpose of this study was to compare the respective loads placed on the remainder of the plant by the anaerobic and aerobic digester overflows. The material passing through the overflow pipe of the secondary anaerobic digester was sampled shortly after sludge was pumped into the digester. These samples were analyzed for COD, nitrogen, ammonia and phosphate concentrations. The anaerobic digester was studied for a 62 day period, following removal of solids from the digester. The data accumulated was compared with data obtained by analysis of the aerobic digester effluent.

Experiments were performed to determine the dewatering characteristics of the digested sludge from the aerobic digester, and sludge from the primary settling tanks. The equipment and procedure used are described in the following paragraph.

Glass tubing with an inside diameter of 4½ inches was used for the dewatering chamber. One end of each of the dewatering chambers was covered with burlap. Screened sand, 14-18 mesh, was placed in each chamber to a depth of 10 inches. This apparatus is shown in Figure 8. One liter of the respective sludge was added to the chamber, taking care to disturb the sand as little as possible. The height of the sludge in the chamber was measured at various intervals of time. Any decrease in volume was attributed to drainage of water into the sand. The measurements were terminated when no change was apparent in the volume of sludge present. Diluted solutions of the perspective sludges were run in the same manner in order to determine the effect of solid content on dewatering rates.

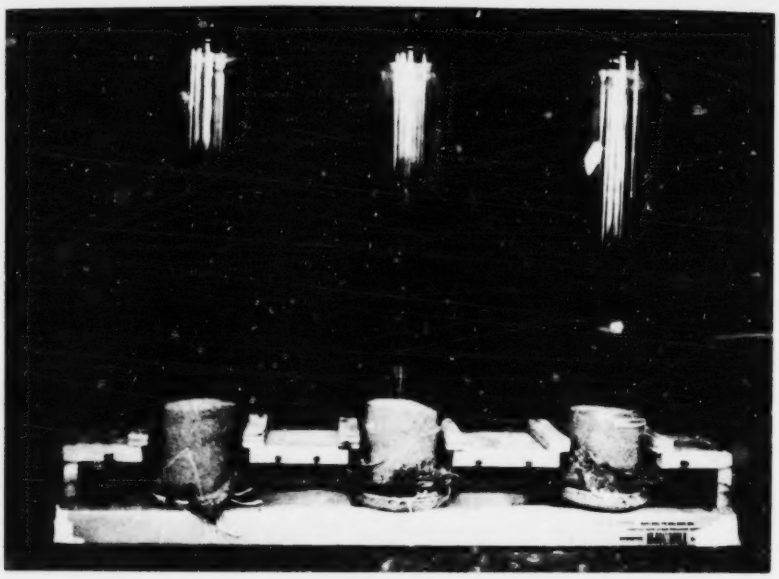

Figure 8. Apparatus for Dewatering Studies

To provide information for a cost analysis of the process, it was necessary to acquire data regarding the electrical power consumed by the aeration and propulsion equipment. An electrical meter was installed in the circuit providing power to the aeration and propulsion equipment to determine the power required to oxidize the organic material in the raw sludge. The power required to operate this equipment in the aerobic digester was recorded together with the pounds to total solids treated. The plant operators kept a record of the time spent working on the sludge treatment facilities. The time spent on this portion of the plant averaged 14.5 man-hours per week. This data was used in calculating labor costs necessary to operate the sludge treatment facility. Labor and electrical power costs were the only expenses which could be directly attributed to the digester. From the information collected the cost of treating sludge by this method was calculated.

SECTION VI

DISCUSSION

Construction of the aerobic digester at River Falls, Wisconsin, began on December 6, 1968, and was completed on September 15, 1969. The digester was placed in operation on September 16, 1969. The channel was filled with effluent from the final settling tanks and approximately 1,500 gallons of activated sludge, obtained from the Pig's Eye waste treatment plant in St. Paul, Minnesota, was added to commence operation.

Mixing and Flow Effects

The mixed liquor velocity in the channel, at that time, was found to be greater than one foot per second. During the first months of operation, as the solids content of the digester liquor increased to 0.6% it was found that the velocity of channel contents decreased to approximately 0.7 feet per second. It was quite difficult to obtain an accurate measure of flow rate as devices normally used for measuring velocity of moving liquids (Gurley Meter) became clogged with solid material. The only suitable means of estimating velocity was by determining the rate of surface movement. In this manner, it was found that the mixed liquor velocity had decreased to approximately 0.4-0.6 feet per second when the solids content of the digester liquid was approximately one percent.

The reduced velocity allowed settling of solids to occur. The plant operators, while performing routine maintenance operations reported deposits of solids on the floor of the digester. The greatest quantities of solids were found near the inside walls of the channel. These deposits were up to 12 inches in depth. This would be expected since, in a closed container the velocity would be a maximum near the outer wall. Two general areas of greatest amount of settling are shaded in Figure 9.

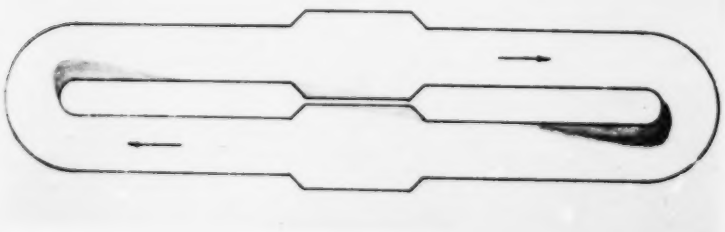

Figure 9. Areas of settling in the aerobic digester.

In view of these observations, a study was carried out to determine the uniformity of the digester contents, both in the horizontal and vertical planes. Duplicate samples were taken at various locations and at different depths at these locations to determine if vertical stratification of solids was also occurring. Figure 10 shows the location of the sampling sites.

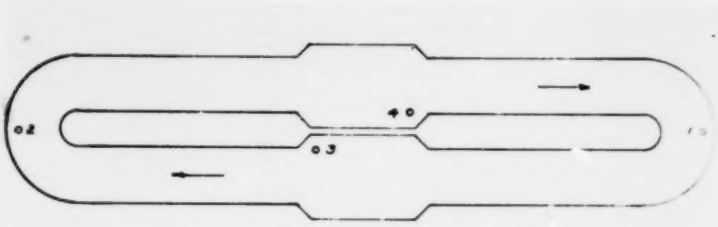

Figure 10. Sampling locations.

Tables 2, 3 and 4 provide evidence of the settling that took place. Table 4 reveals that the solids were accumulating near the corners in the digester. That is, the total residue levels found at the ends of the oval channel (sites 1, 2; Figure 10) were greater than those determined near the aerators and flow inducers (sites 3, 4; Figure 10). This condition existed because the power expended to move the material in the digester was not sufficient to ensure a velocity of 1.0 feet per second around the 180^{o} turn at each end of the channel.

Table 2. Total Residue of Mixed Liquor at Various Sampling Sites

	Total Residue, ppm			
Site	1	2	3	4
January 26, 1970	8800	9240	5700	6100
January 31, 1970	8630	9070	6240	6350

The COD of the mixed liquor varied in the same manner as the total residue at the various sampling sites. Table 3 gives the results of the COD determinations at various sites.

Table 3. COD of Supernatant Liquor at Various Sampling Sites

	COD, ppm			
Site	1	2	3	4
January 26, 1970	94?	989	489	514
January 31, 1970	795	787	598	657

The information in Table 4 was useful in determining the stratification in the vertical plane. The digester was sampled at various depths to determine if significant differences in the total residue existed. This data shows that the solids were not being kept in suspension by the propeller type hydraulic flow inducers and indicated again the need for better propulsion equipment.

Table 4. Total Residue of Mixed Liquor at Various Depths at Site 3.

Depth	Depths at Surface	2 feet	3 feet	4 feet
Total Residue ppm	6620	6730	6950	7240

Several months after the digester was placed in operation, a great deal of floating material appeared. This floating material formed a solid mat, completely covering the channel surface in the areas shown in Figure 11.

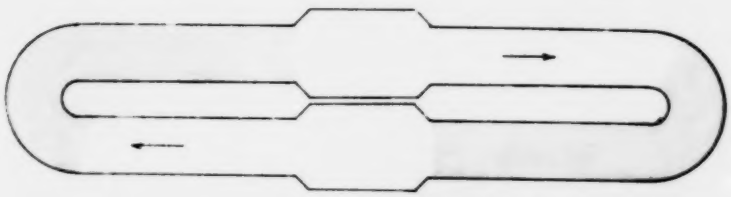

Figure 11. Extent of scum mat.

It was felt that the condition in the putrescible solids which settled became anaerobic and the gas formed during anaerobic decomposition, collected in and on the solid matter, causing these solids to rise to the surface. Once a sufficient quantity of solid material was present on the surface, the surface aerators retarded its movement, as the spray impinging on the surface of the channel liquor in opposition to the direction of flow in the channel prevented movement of floating material through this region.

Due to the aforementioned problems, the data collected prior to April 1970 is questionable and was not used in the evaluation of process effiency.

During April 1970, the propellor type flow inducers were replaced by two cage rotors. Each of the cage rotors was 7 feet in length and these were placed end to end in one of the widened sections of the channel. The velocity of the channel contents, as measured by surface movement, was found to be in excess of one foot per second. The plant operators reported that large amounts of solids were no longer present on the digester floor. Samples taken at selected sites gave COD's which were in good agreement (Table 5). Analyses of samples taken at various depths from sampling site number 2 also indicated great reduction in vertical stratification with the increased velocity. The COD's and total solids content of these samples is tabulated in Table 6.

Table 5. COD of Mixed Liquor of Various Sampling Sites.

Site	COD, ppm
1	4410
2	5020
3	5040
4	5020

Table 6. Total Residue and COD at Various Depths at Sampling Site Number 2.

Depth	Total Residue, ppm	COD, ppm
Surface	8830	6920
2 feet	8890	7000
3 feet	8560	6820
4 feet	8780	6610

Since there was no control over the dissolved oxygen as supplied by the cage rotors, the surface aerators were used to supplement the oxygenation capacity of the cage rotors and provide a means of controlling the DO content of the liquor. This was possible since the oxygenation capacity of the cage rotors was insufficient to support the process and provide a detectable DO in the mixed liquor.

Based on the previous evidence it appears that the cage rotors are effective in providing the velocity of mixed liquor necessary to retain solids in suspension while the original, propellor type flow inducers were not. A second advantage of the cage rotors was that the DO content of the mixed liquor did not vary as widely as previously since the cage rotors aerate continuously.

Oxygenation Performance

Prior to the installation of the cage rotors, when the propellor type flow inducers and surface aerators were in operation, the dissolved oxygen varied widely around the channel. Samples of mixed liquor were taken at selected sites around the digester and the dissolved oxygen determined. From the results obtained it appeared that about one-half of the mixed liquor was receiving adequate aeration and the other half was not. It was postulated that this was due to the "plug" flow in the channel where there was little horizontal mixing of the channel contents. This resulted in the following sequence of events. When oxygen deficient mixed liquor reached the location of the DO probe the aerators were activated. The aeration continued until an aerated "plug" reached the DO probe at which time the aerators are shut down. Since the DO probe was located midway between the two aerators, the oxygen deficient "plug" was reaching the second aerator at that time. However, the aerators were not reactivated until the oxygen deficient "plug", from the opposite end of the channel reached the DO probe. By this time the first oxygen deficient "plug" had moved past the second aerator. As a result, certain "plugs" were aerated repeatedly while others received little if any aeration. During the month of October 1969, dissolved oxygen measurements at several sites were made frequently. The results are tabulated in Table 7. The sampling locations were the same as those shown in Figure 10. Examination of this data revealed a wide variation in the DO content of the mixed liquor. This may have been partially due to depletion of DO as the mixed liquor moved around the channel and partially due to the "plug" effect. Definite proof of this was not obtained during this investigation as simultaneous measurement of DO at several sites would have been necessary. Equipment for doing this was not available. Installation of the cage rotors improved this situation as the cage rotors aerate continuously.

Temperature Effects

Although retention of solids in suspension during the first winter of operation was a major problem, other evidence indicated the process was severely affected by the low temperature of the mixed liquor dur-

Table 7. Dissolved Oxygen in Mixed Liquor[1]

Date	Settleable Solids	D gester Temp. °C.	Site 1	Site 2	Site 3	Site 4	Avg.
Sept. 29							
Sept. 30							
Oct. 1							
Thur. 2	18%						
Fri. 3							
Mon. 6[2]	24%						
Tues. 7	26%						
Wed. 8	30%						
Thur. 9	32%	19.2	1.9	---	4.1	---	3.0
Fri. 10	34%	20.0	1.7	---	4.3	---	3.0
Mon. 13	42%	18.0	2.9	---	4.8	4.2	4.0
Tues. 14	50%	17.5	3.6	4.0	5.0	3.9	4.1
Wed. 15	63%	18.0	3.2	---	5.6	3.6	4.1
Thur. 16	71%	17.5	1.4	1.6	3.4	1.9	2.1
Fri. 17	68%	17.0	3.6	3.2	4.2	2.5	3.4
Mon. 20	74%	18.0	1.5	1.6	3.2	1.8	2.0
Tues. 21	74%	18.5	No Oxygen At Any Site				
Wed. 22[3]	74%	19.0	No Oxygen At Any Site				
Thur. 23	---	----	---	---	---	---	---
Fri. 24	---	----	---	---	---	---	---
Mon. 27	33%	17.5	3.7	---	5.0	3.0	3.9
Tues. 28	35%	16.8	2.2	---	4.8	3.8	3.6
Wed. 29	36%	16.5	3.6	3.8	5.2	4.4	4.3
Thur. 30	38%	15.7	2.9	2.7	4.2	3.1	3.0
Fri. 31[4]	40%	16.5	No Oxygen At Any Site				

1-All DO concentrations reported in parts per million.
2-Aerators off several hours while ditch was skimmed.
3-Ditch dumped.
4-DO Level zero.

ing that time. The digester contents responded rapidly to changes in the ambient air temperature. The data in Table 8 shows that temperature changes of the digester contents occurred within twenty four hours of a significant change in outside temperature.

Table 8. **Comparison of the Outside Air Temperature and the Temperature of the Mixed Liquor.**

Date	Outdoor Temp. °F High	Low	Temp. of Mixed Liquor °F
January 13	17	1	42
14	13	5	44
15	27	13	45
16	15	- 2	45
19	-13	-36	42
20	-11	-23	41
21	-10	-32	40
22	17	-13	41
23	16	-16	44
24	29	5	46

During the periods of time covered by this Table, the temperature of the digester contents ranged from 40-46°F In fact, from January 1, 1970 to March 15, 1970, the temperature of the digester contents never reached a temperature of 50°F. These low temperatures for extended periods of time resulted in ice formation on the surface of the mixed liquor. This problem was greatest on the end of the digester farthest removed from the heated wier housing. The ice in this area would reach a thickness of approximately one foot. Solids were trapped in this ice during its formation. As the digester contents warmed, the ice melted and the volatile solids content and COD increased appreciably. Ice formation remained a problem throughout the winter. A temperature of 50°F was deemed necessary to allow aerobic digestion to take place at a satisfactory rate (Keefer, 1962).[18] Results of this investigation also demonstrated the need for maintaining a temperature in excess of 50°F (Table 9). Based on this information, a heat exchanger was installed in the digester during the second winter of operation to maintain the temperature above this value. Effect of the increased temperature cannot be evaluated quantitatively as routine analysis were not performed during the time the heat exchanger was in operation. However, the sludge was being digested to a greater degree as evidenced by appearance, odor and settling of solids. The characteristics of the digested sludge was much as that produced during the warmer months when the process operated efficiently.

Examination of the data in Table 9 indicates that even with a sufficient rate of flow the process was not efficient at temperatures typical of Wisconsin winters. The cage rotors were in operation ditches

10, 11 and 12 providing an adequate flow rate in the channel. A general trend was established in which the reduction of volatile residue, COD and nitrogen in the digester was substantially less as the average temperature of the mixed liquor decreased from 72°F to 48°F.

Table 9. Process Efficiency of Ditches 10, 11, 12

Ditch Number	Percentage Reductions			Average Mixed Liquor Temperature °F
	Volatile Solids	COD	Nitrogen	
Ditch 10				
May 29 - Oct. 1				
0- 25 days	47.0	56.0	31.0	72
57- 70 days	56.4-59.5			
70- 90 days	59.5-63.0			
0-126 days	64.7			
Ditch 11				
Oct. 26 - Nov. 23 0- 29 days	33.9	40.9	16.8	54
Ditch 12				
Jan. 6 - Jan. 29	21.7	44.6	30.8	48

The results, as summarized in Table 9, show a significant decrease in the efficiency of the process during periods of low temperature and suggest a need for an auxillary heat source during these times. Bench scale operation of an aerobic digester (Appendix D) yielded information confirming this conclusion.

Process Efficiency

The ambient air temperature exerts a significant effect on the temperature of the channel contents. The direct relationship between process efficiency and temperature dictates the necessity of considering the warm and cold weather studies separately.

When discussing process efficiency, parameters for discussion include bacterial population as measured by the standard plate count; the dissolved oxygen content of the mixed liquor and its effect on 1) volatile solid, COD, and nitrogen reductions and 2) the presence of inorganic plant nutrients. Table 9 provides information concerning temperature, overall process efficiency and the number of days each ditch was operated. A record of the data acquired during ditch numbers 10, 11 and 12

appears in Appendices A, B and C respectively.

For purposes of discussion, the warm weather study (D-10) was divided into four periods based on the levels of dissolved oxygen being maintained in the mixed liquor. Table 10 shows the daily dissolved oxygen limits for D-10. During periods one and three, the digester contents were more highly aerated than during periods two and four.

Table 10. Daily DO Limits of Ditch 10 and Corresponding Concentrations of Nitrate and Phosphate

Period Number	1	2	3	4
Days of Ditch	40-57*[1]	57-70	70-100	100-126
DO Limits in ppm	.75-1.75	.75-1.25	1.25-1.75*[2]	.75-1.25
Nitrate in ppm				
Hi	30.1	14.7	29.7	none
Low	7.0	4.2	0.6	none
Ave.	18.7	7.1	12.3	none
Phosphate in ppm				
Hi	104	66	115	76
Low	65	54	56	46
Ave.	82	62	88	61

Note: 1 - oxygen limits day 0-43 were .75-1.25

2 - probe was recalibrated day 99 and found to be monitoring oxygen concentration 3 ppm too low.

The principle reason for changing the oxygen limits can be attributed to the amount of nitrate which would begin to build up in the channel liquor after an extended period of high aeration. On two occasions, the nitrate concentration was great enough to be considered a problem. These instances both occurred during periods of high aeration (periods 1 and 3 from Table 10). The computed average for nitrate during period 1 was 4.8 ppm. Nitrate concentration first began to increase markedly on day 42 when it rose from 9.3 to 16.3 ppm. During the first aeration period, nitrate remained in a concentration range from 16-30 ppm.

The upper limit on dissolved oxygen was lowered from 1.75 to 1.25 on day 57 in an effort to lower nitrate concentration. The elapsed time from days 57-70 is referred to as period 2. At this time, the probe was also calibrated and found to be reporting oxygen in concentrations 4 ppm too low. This strongly suggests that the actual dissolved oxygen of the channel was considerably higher than the upper limit of 1.75 ppm as set on the DO meter. It is not known when faulty operation of the probe began,

but it appears reasonable to assume that this paralleled the rapid increase in NO_3^- beginning on day 43.

On day 70, in order to verify the apparent direct influence of oxygen on nitrate concentration, the limits were raised from .75-1.25 ppm to 1.25-1.75 ppm. In response, nitrate rose rapidly to 16 ppm and maintained a range of 16-30 ppm for days 80-89. The limits were reset on day 100 to .75-1.25 and the nitrate concentration dropped to a negligible amount by day 103, where it remained for the duration of the ditch. It should be noted that on day 99 the probe was once again reporting oxygen concentration 3 ppm too low. The DO before, during and after days 43-55 and 80-89 together with the nitrate present at those times indicated that levels of aeration above 2 ppm resulted in large amounts of nitrate.

The dissolved oxygen concentration in the mixed liquor was of considerable importance to the process efficiency. The adjustment of the DO limits maintained in the digester also provided valuable information concerning volatile solids, COD and nitrogen reductions. From the data obtained, it appears that nitrogen reduction is closely related to volatile solids and COD reductions. For this reason, only an overall reduction in nitrogen is reported (Table 9).

Volatile solids in the channel liquor increased steadily until reaching a plateau on approximately day 70. Figure 12 is a graphical representation of the manner in which volatile solids accumulated in ditch 10. The plateau was maintained for a period of about 20 days until day 90 to day 70. Since loading rates were approximately the same throughout the duration of the ditch it appears the total load had exceeded the process capabilities. This corresponds to a decreasing nitrate concentration which would indicate that the aeration capacity was being exceeded.

Two factors seem to be responsible for this "plateauing effect". First no sludge was added to the digester on days 77, 78 and 81 because the raw sewage contained an appreciable amount of fuel oil. Without an addition of food, the bacteria had a longer period of time in which to act upon the less readily degradable substances. Secondly, the limits on the DO meter were raised on day 70 and the plateauing region occurs over the same span of time as that for aeration period 3 (Table 10).

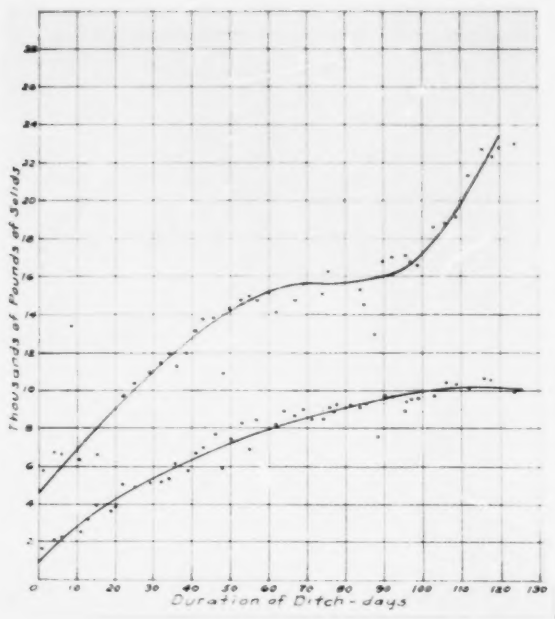

Figure 12. Accumulation of Volatile Solids in Ditch 10

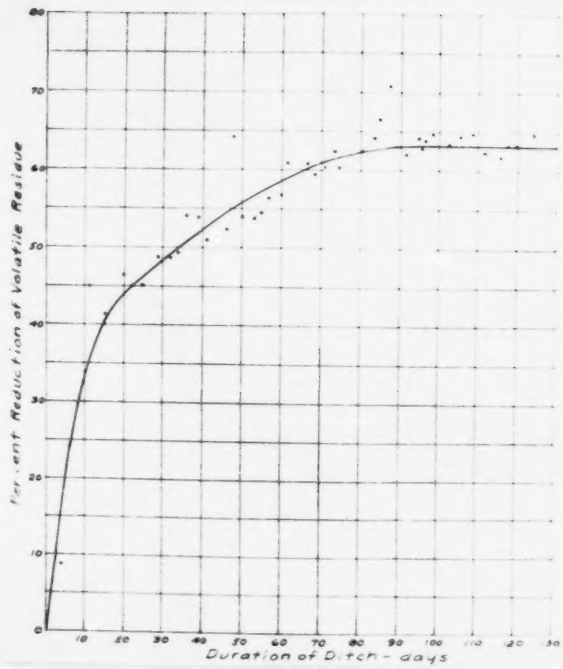

Figure 13. Volatile Solids Reduction Versus Day of Ditch (Ditch 10)

Regardless of the parameter considered, a certain length of time was required for the ditch to mature before a satisfactory reduction occurred. This time period was influenced by variations in temperature, circulation velocity and DO. With inadequate circulation velocities, all of the solids will not remain in suspension to be properly aerated. Further adverse effects on efficiency and bacterial population size were exerted by low temperature. This maturing phase is graphically illustrated in Figure 13, which is a plot of percent volatile solids reduction vs day of the ditch. The volatile solid reduction was initially very low and did not exceed 40 percent until the 11th day. Low percentage reductions indicate little activity by bacteria or an inadequate population size. The efficiency in volatile solid removal and bacterial population size appear to be directly related. It was apparent that some minimum level of solids (available food material) must be available between sludge additions if a large population was to be maintained.

The bacterial population may vary significantly within a days operation (Figure 14). Two hours after pumping sludge into the digester, the initial population, in each of five separate studies, increased drastically. Then, the number of bacteria decreased to a population

approximately equal to that found prior to sludge addition. Investigation of the phenomenon in the laboratory showed this effect to be primarily due to large numbers of bacteria present in the raw sludge (Appendix D). When the population exhausted this readily degradeable material, a decline in total count was observed. Less readily degradable material appeared incapable of maintaining a large population. This suggested the necessity for smaller but more frequent additions of sludge. Similar results were reported by Lawton and Norman[26] who decided that an infrequent feed basis of operation followed by a rather prolonged aeration before further feeding resulted in poorer volatile solid reduction. They concluded that prolonged starvation of the microorganism would severely reduce the number of viable cells.

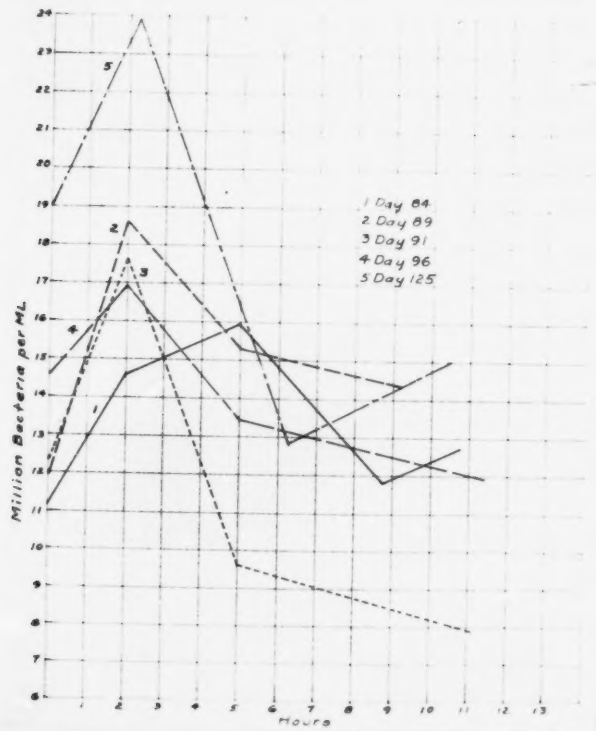

Figure 14. Variations in Total Bacteria Population Within a One-Day Time Interval

Table 11 shows the population between days 11 and 40 remained relatively constant and the percentage reduction for volatile solids during the same 29 days increased only 6% (45-51 percent). Day 40, however, marked the first day in a period (days 40-57) in which the population expanded markedly, reaching a peak of 34.3 million/ml on day 55. During this same period of time (15 days), the volatile solids reduction increased by 5%. It will be recalled that aeration

during this period was in excess of 2.0 ppm and that large amounts of nitrate were being produced. Such evidence seems to indicate that a large population, which can effect a greater reduction, will occur only during extended periods of high aeration.

Table 11. Bacterial Populations of Ditch 10

Ditch Day	Million Bacteria per ml	Ditch Day	Million Bacteria per ml
12	3.5	55	24.7
14	4.5	57	18.5
20	3.5	61	8.4
25	4.6	62	12.0
28	5.4	63	10.2
32	5.5	70	8.3
34	5.7	84	11.1
40	8.2	85	12.2
42	10.4	89	11.8
46	8.7	90	17.3
49	14.6	91	12.2
51	31.9	92	5.2
53	29.9	96	14.5
54	34.3	97	9.9
		125	18.9

In reference to Table 9, it will be noted that the overall percent reduction increased only slightly (56.4-59.5 percent) from day 57 to day 70, but that a marked increase occurred between days 70 and 90. As evidenced by the decreasing amount of nitrate (Table 10), the period encompassing days 57-70 was one of lower aeration. Bacterial population size decreased during this period from a high of 18.5 million/ml on day 57 to 8.3 million/ml on day 70. The period of greater reduction (days 70-90) correlated to one of increased aeration (Table 16) and nitrate formation. The bacterial population increased from 8.3 million/ml on day 70 to 17.3 million/ml on day 90. The efficiency of this period, however, may have been affected by the lack of sludge addition on days 77, 78 and 81. The overall percentage reduction after day 90, during a period of lower aeration, decreased to a final value of 64.7 percent.

An important consideration in solids reduction is the formation of fixed residue. A decrease in volatile solids should be accompanied by an increase in fixed residue. Figure 12 illustrates that the pounds of fixed residue did increase until day 100. After day 100, pounds of volatile solids increased rapidly while fixed residue remained nearly constant.

In view of the small increase in percent reduction of volatile solids between days 57 and 70 and an actual decrease after day 90, it seems apparent that extended periods of aeration above 2.0 ppm will maintain a larger bacterial population and effect a greater reduction in volatile solids.

The overall reduction in chemical oxygen demand for ditch 10 was 67.8 percent (Table 15). A reduction of 60 percent was reached on day 22 and a range of between 60 and 65 percent was maintained until approximately day 70. From day 70 to the end of the ditch the reduction range remained between 65 and 72 percent with the higher values consistently occurring during the period of great aeration (days 70-90). After day 100, it was noted that COD began to accumulate at a much greater rate than at any other time during the ditch. This suggests that COD reduction was occurring to a lesser extent that at previous times. It should be recalled that pounds of volatile solids were also increasing rapidly at this time.

The COD of the clear supernatant liquor removed from ditch 10 (Appendix A) fell within a range of 98-300 ppm with the average being 148 ppm. The relatively high COD of the supernatant removed may have to be tolerated in order to achieve the reduction appearing in Table 9.

The reduction of nitrogen as calculated did not show any appreciable variation at different concentrations of dissolved oxygen. The overall nitrogen reduction of ditch ten was 55.2 percent.

It is of interest to report that ammonia in the effluent was consistently in the range of 0-5 ppm and appeared in negligible amounts during the periods of high aeration. The increase of organic nitrogen in the mixed liquor of the ditch was erratic but steady. The nitrate present was of concern only when aeration was high.

Phosphorus, as with nitrate, varied directly with the amount of dissolved oxygen being maintained in the mixed liquor. The maximum, minimum and average phosphate ion concentration during four different periods of aeration, are given in Table 10.

The average phosphate ion concentration during days 57-70 and 100-126 were respectively 62 and 61 ppm. Both were periods of low aeration, when the upper oxygen limit on the DO meter was set at 1.25 ppm. At oxygen concentrations above 2.0 ppm (during days 43-57 and 70-100), the average phosphate ion concentration increased to 82 and 88 ppm, respectively. Greater amounts of phosphate were produced during periods of high aeration and volatile solids reduction. The amount of phosphorus entering the plant due to detergents must be considered to be reasonably constant at all times. Therefore, the increase in phosphate ion concentration during periods of high aeration must be due to the release of phosphate from organic sources as a direct result of a higher DO content.

The effect of prolonged periods of low temperature on the process can clearly be seen in Table 9. This table summarizes the overall efficiencies in volatile solid, COD and nitrogen for ditch numbers 10, 11 and 12. In order to eliminate the duration of the ditch as a factor in achieving the final overall efficiency, the efficiency for ditch 10 was calculated at day 25. This compares favorably with the operational periods of 29 and 23 days for ditches 11 and 12, respectively. The dissolved oxygen was not believed to be a limiting factor during the cold weather studies. The probe was calibrated frequently to avoid faulty operation and the limits on the DO meter remained set at 1.0-2.5 ppm for both ditches.

Table 9 indicates a relationship between temperature and the reductions realized in the channel. It appears that a decrease in reduction follows a decrease in temperature. Ng, Ingraham and Marr reported in 1962 the damage and depression of activity in organisms subjected to low temperatures.[27] Ng also reported in 1968 the effects of decreasing temperature on cell yields.[28]

The bacterial population which appeared inhibited by the amount of oxygen during warm weather was actually greater during cold weather studies. Population studies on ditch 11 (Table 12) revealed that the population was actually increasing at the time of termination.

Although the population was larger than for ditch 10 (Table 11), its activity was minimal. Pour plates of the mixed liquor incubated at 35°C revealed that colonies were of an extremely small nature even after 48 hours of incubation. Bacterial pour plates of ditch 10 (ave. temp. 22°C) did not demonstrate this phenomenon.

Table 12. Total Population of Bacteria in Ditch 11 (Ave. temp. 12.3°C)

Day	Bacteria in million/ml	Day	Bacteria in million/ml
2	3.4	17	23.7
11	22.4	24	29.9
16	13.3	27	33.6

The decrease in activity of the bacteria was very apparent in the reduction of volatile solids. As the temperature of operation decreased in the order of 22°C, 12.3°C and 9.0°C the reduction occurring at these temperatures decreased in the order of 45.2, 33.9 and 21.7 percent. The overall reductions of COD and nitrogen were also markedly lower during cold weather.

Further evidence of little bacterial activity is provided by the con-

sistently lower production of plant nutrients as the ditch temperatures declined. As demonstrated in ditch 10 (Table 10) if aeration is adequate, the digestion of organic phosphorus and nitrogen containing compounds released large quantities of phosphate and nitrate.

It is possible that during the cold weather studies, the high populations found were due to psychrophilic bacteria which may not possess the same ability to handle domestic sewage solids as the bacteria found in warm weather conditions. If this is true, one might expect lower reduction in volatile solids, COD and nitrogen to be the case.

The most important factor in process efficiency was temperature. Even though a large bacterial population was present during cold weather studies, it was ineffective in producing satisfactory reductions. However, once temperature became conducive for biological activity to proceed, dissolved oxygen became the limiting factor. By changing the dissolved oxygen concentration, one could observe a direct response in bacterial population size and hence the various percentage reductions.

Sludge Dewatering Characteristics

It was observed that the digested sludge dewatered very slowly after being pumped onto the drying beds. It was reasonable to presume that a great deal of organic residue, from previous dumpings (over a 6-7 year period), had accumulated in the drying beds. Prior to this investigation, untreated sludge was dumped onto the drying beds and worked into the soil. This hygroscopic material swells when wetted and seals the upper stratrum of drying beds. This retarded the dewatering of any sludge placed on the drying beds at a later time. It was evident that putresible solids remain in the sand for long periods of time. After periods of rainfall and/or during the spring thaw, the odors present in this area were clearly those associated with anaerobic decomposition.

The drying capacity of the sand in the drying beds was tested. Soil cores were taken from three different sites on the drying area using a soil borer. Each sample was carefully transferred to separate glass chromatography columns. The height of each solid sample was 17.0 cm. A further column, serving as a control, was set up containing 17.0 cm of washed sand. The chromatography tubes extended about 10.0 cm above the soil sample, providing space for adding water. Distilled water was then added to each tube and the time elapsing before the water dripped from the bottom was recorded.

Water percolated through the washed sand (control) and dripped from the bottom of the tube within 60-65 seconds. The same time was recorded whether the columns were dry-packed or moistened prior to the test. The water did not appear to move at all through the drying bed samples. Several hours after the water was added there was no indication of any water movement through these samples. A small beaker was placed,

inverted, over the open end of the chromatography columns and they were left undisturbed for several days. After one week the only changes observed were some air breaks in the soil column apparently a result of gas formation by microorganisms. After 10 days the experiment was terminated. At that time there was no indication that the water had progressed any farther down the column that it had initially after the first few seconds.

Laboratory studies were carried out using clean sand to eliminate the effect of residual organic material and obtain quantitative information about dewatering characteristics of sludges. These studies were performed as described in the Experimental Phase of this report. The results of these experiments (Tables 13 and 14) clearly showed that the digested sludge dewaters more slowly than does raw sludge. However, it is postulated that repeated use of the same sand, for dewatering raw sludge, will result in a buildup of colloidal matter causing the dewatering rate to be greatly decreased. This should not occur with digested sludge as there is very little colloidal matter present. Of course, the sludge cake formed with the first addition of sludge would have to be removed before the second addition of sludge, if this premise is to be tested. (Experiments are underway to support this supposition).

Table 13. Dewatering Characteristics of Digested Sludge

Time (min.)	Volume Remaining in Column (cm^3)		
	1	2	3
0	1000	1000	1000
10	870	790	700
20	790	680	550
30	750	600	400
40	720	540	290
50	670	470	180
60	640	420	-
70	620	360	-
80	590	320	-
90	580	250	-

[1]-Percent solids (total) dry weight: No. 1, 1.7%; No. 2, 0.85%; No. 3, 0.43%

Table 14. Dewatering Characteristics of Raw Sludge[1]

Time (min.)	Volume Remaining in Column (cm^3)		
	1	2	3
0	1000	1000	1000
5	-	-	650
10	820	770	530
15	-	-	460
20	750	680	410
30	700	650	350
40	650	570	310
50	620	520	290*
60	590	480	-
70	-	410	-
75	560	-	-
80	-	380	-
85	470	330	-
100	500	280*	-
120	460	-	-
150	380	-	-
180	340*	-	-

*At this point the solid cake no longer had liquid standing above it.

[1]-Percent solids (total) dry weight: No. 1, 1.45%; No. 2, 0.73%; No. 3, 0.37%

In summary, it would appear that raw sludge dewaters most rapidly. However, unless the sand is replaced periodically the drainage capacity of the sand is greatly reduced. At the present time, it is not known whether the same would be true for digested sludge. From the data obtained, it is quite obvious that the dewatering rate decreases as the thickness of sludge cake increases.

Analysis of Costs

The cost of designing and constructing the sludge treatment facility is tabulated in Table 15.

Table 15. Design and Construction Costs

Item	
Engineering and Legal Fees	8,160.00
Construction (General)	$131,792.43
Construction (Electrical)	7,784.51
DO Analyzer/Controller	1,582.00
Hoist (for Flow Inducers)	270.85
Sludge Flow Meter	990.00
Miscellaneous	1,587.48
	$152,167.27

The cost of replacing the original flow inducers with cage rotors was $6,554.60. The cage rotors were purchased for $4,075.00 and the associated electrical switchgear for $2,479.60 (including installation) bringing the total cost of the facility to $158,721.87.

The operating expenses for operation of the aerobic sludge treatment facility for D-10 have been determined. These costs were incurred over a period of time extending from May 29, 1970 to September 30, 1970. This period of time was chosen for the analysis as it represents the period of greatest efficiency. It therefore shows the minimum cost of sludge treatment in this facility. The costs of the electrical power and plant operators time are the only items to be considered. During this period a total of 43,310 KWH of electrical power were used. The man-hours expended averaged 14.5 hours/week for eighteen weeks. The operators recorded their time spent on the sludge treatment facility. The expenses incurred are shown in Table 16.

Table 16. Operating Costs for Ditch 10

Operation	Time (hrs./wk.)
Solids removal	2.5
Maintenance (Flow Inducers)	2.0
Maintenance (Aerators)	2.0
Maintenance (General)	4.0
Work related to the research effort	4.0
	14.5

The following unit costs were used in calculation of operating expenses.

Electrical Power	1.5¢/KWH
Labor	$2.965/hr.

Total operating costs for 18 week period

43.310 KWH x $0.015/KWH $649.65

14.5 man-hours x 18 weeks x $2.96/man-hour week = $773.86

$1,423.51

During the time period in which these costs were incurred, a total of 678,800 gallons of sludge, containing 39 tons of solids, were treated. Cost per ton of solids (dry weight) treated was determined to be $36.50 /ton.

Comparison of Aerobic and Anaerobic Digesters

Comparison of the load placed on the remainder of the treatment plant by the aerobic digester as compared to an anaerobic digester (Hudson, Wisconsin) was made. During the early days of this study the anaerobic digester was not being heated. As a result, there was no mechanical agitation of the digester contents. On the 37th, 51st and 62nd day of operation the circulating pumps were operating and digester contents heated, but for only those days. The data in Table 3 show that when the heater and circulating pumps were operated all components normally present in the overflow liquor increased dramatically. When the circulating pumps were shut down the mixed liquor flowing from the secondary digester outlet was considerably lower in COD, total solids, organic nitrogen and ammonia content (Table 18). The values in Table 17 are average values of the digester contents removed during the period indicated. This suggests a lower overall process efficiency since the ammonia is a soluble component and should be present at an increasing level. Examination of the value obtained for total solids content in the digester overflow demonstrates that solids do settle in the digester. This would explain the lowered efficiency because when

solids settle the surface area available to support microbial activity is decreased.

Table 17. Data From Anaerobic Digester

Date	Day of Operation	COD (ppm)	Organic Nitrogen (ppm)	Ammonia in (ppm)	Phosphate (ppm)	Total Residue ppm	pH
June 11	20	2710	39	110	170	1740	
14	23	2720	15	110	80	1740	
16	25	2580	13	110	80	1600	5.9
18	27	2560	18	120	80	1860	
21	30	2580	22	110	90	1560	5.4
23	32	2590	16	110	110	1580	
25	34	2320	27	130	180	1580	5.7
28	37	2530	65	150	140	2390	
July 1	40	2540	27	130	120	1570	
6	45	2350	24	110	100	1470	
8	47	2160	24	110	110	1240	6.0
12	51	4100	24	124	120	2680	6.1
15	53	3550	20	110	100	2240	6.1
19	57	3470	20	110	120	2370	6.4
21	60	3390	23	100	120	2160	6.3
23	62	3950	28	120	120	2510	6.5

The anaerobic digester puts a much greater load on the remainder of the treatment plant than does the aerobic digester (Table 18). The only component present at higher levels in the aerobic digester supernatant is nitrate. However, the supernatant liquor from the anaerobic digester is recirculated through the primary settling tanks and trickling filter. As the ammonia is converted to either nitrogen gas or nitrate, in the trickling filter even this advantage of the anaerobic digester is lost. In summary, this comparison clearly demonstrates that the quality of effluent from an anaerobic digester is inferior to supernatant removed from the aerobic digester.

Table 18. Comparison of the Overflows of an Aerobic Digester and an Anaerobic Digester

Ditch Number	Total Solids	COD ppm	Organic Nitrogen ppm	Ammonia ppm	Nitrate ppm	Phosphate ppm
Ditch 10						
25 days	negligible	126	6.2	1.4	2.8	115
62 days	negligible	160	5.2	1.4	10.8	59
Ditch 11						
27 days	negligible	99	4.5	0.1	0.4	40
Ditch 12						
23 days	negligible	155	3.3	1.4	0.8	26
Anaerobic Digester						
62 days	1890	2880	25.3	117	negligible	115

SECTION VII

ACKNOWLEDGEMENTS

The research on this project was accomplished in the facilities provided by the University of Wisconsin-River Falls and the city of River Falls, Wisconsin. The major portions of the research and analyses were carried out in lab space provided by the University of Wisconsin-River Falls. In addition, the city of River Falls provided certain other necessary facilities at the waste treatment plant site. The co-directors worked closely with several community and campus personnel and wish to acknowledge here their cooperation;

Dr. Milan Wehking, Co-director
Dr. Jack M. Bostrack, Co-director
Mr. Joe Maxwell, City Utilities Manager
Mr. Kermit Wollan, Utilities Commissioner
Mr. Louis Breimhurst, F.W.P.C.A. Project Officer
Mr. Clete Henriksen, Business Manager, University of Wisconsin-River Falls
Dr. Orin Halverson, Consultant
Members of the Utility Commission, River Falls, Wisconsin

The sludge treatment facility was based on a process designed by Dr. H. O. Halvorson, Minneapolis, Minnesota. The plant design and specifications were drawn up by Mr. Randolph L. Smith, consulting engineer, St. Paul, Minnesota, in conjunction with Dr. Halvorson and Mr. Carroll Grubb, City Engineer, River Falls, Wisconsin. A contract for the general construction was let to Lysne Construction, Blooming Prairie, Minnesota, and construction began December 6, 1968, although significant progress toward completion of this facility was not made until Spring 1969. The necessary electrical work was performed by Linner Electric, Stillwater, Minnesota.

The various testing, analyses, and compilation of data was accomplished under the able direction of Mr. Larry J. Monette, Senior Chemical Analyst and his capable assistant Mr. Larry Hansen. In addition to their in-lab studies and analyses these two investigators maintained close surveillance of the waste treatment plant operations and liason with the plant managers.

Last, but by no means least, we would like to extend our appreciation to the managers of the waste treatment plant; Mr. Russell Bowen, Mr. Jerry Larson and Mr. Conrad Segerstrom. When minor, or major, changes in operation were needed these persons could always be relied upon to accomplish the task in a professional and skillful manner.

SECTION VIII

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SECTION IX

GLOSSARY

Ditch No. 1, 2, 3, etc. (D-1, D-2, D-3, etc.) - refers to specific time intervals of varying number of days between sludge wasting events.

Mixed Liquor Velocity - the rate of movement of the mixed liquor in the closed channel.

Semi-Continuous Process - process in which more than one addition of raw sludge was added each day but withdrawals from digester made less frequently.

Skimming - refers to removal of supernatant liquor from digester after allowing solids to settle. Accomplished by means of adjustable overflow wier.

SECTION X.

APPENDIX A

Table 19. Data For Ditch 10

May 29 - Oct. 1, 1970			126 days
Calendar Day	Ditch Day	Ditch Characteristics	
		Temperature °C	Volume in Digester Gallons
May 29	1	17.0	159,100
30	2	20.0	165,200
31	3	21.9	167,400
June 1	4	20.5	172,200
2	5	21.0	178,100
3	6	21.1	183,900
4	7	20.0	191,900
5	8	21.1	198,200
6	9	21.1	203,800
7	10	21.1	207,700
8	11	23.3	176,200
9	12	22.2	182,300
10	13	23.3	188,000
11	14	25.5	190,300
12	15	25.5	195,800
13	16	23.3	189,300
14	17	23.3	192,200
15	18	23.8	167,400
16	19	23.8	174,400
17	20	25.0	180,500
18	21	25.0	186,800
19	22	21.1	193,400
20	23	20.0	199,400
21	24	20.0	202,500
22	25	20.5	205,700
23	26	20.0	167,400
24	27	21.0	174,600
25	28	21.0	180,700
26	29	20.0	187,900
27	30	21.1	194,100
28	31	21.1	197,500
29	32	23.3	201,000
30	33	25.5	207,700
July 1	34	26.6	167,400
2	35	26.6	172,800
3	36	24.4	178,100
4	37	24.2	183,600
5	38	23.2	186,000
6	39	18.3	189,000
7	40	20.0	176,200
8	41	21.1	180,800
9	42	21.1	186,800

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Table 19. Data For Ditch 10

May 29 - Oct. 1, 1970 — 126 days

Calendar Day	Ditch Day	Ditch Characteristics	
		Temperature °C	Volume in Digester Gallons
10	43	23.1	192,100
11	44	23.8	197,500
12	45	25.0	199,600
13	46	25.5	202,300
14	47	26.1	209,800
15	48	26.1	167,400
16	49	23.8	174,700
17	50	23.8	180,500
18	51	23.3	187,300
19	52	23.3	167,400
20	53	22.2	171,800
21	54	21.1	177,400
22	55	21.1	183,100
23	56	21.1	189.500
24	57	21.1	171,800
25	58	21.1	178,800
26	59	20.1	184,300
27	60	24.4	188,600
28	61	25.5	171,800
29	62	26.6	177,500
30	63	26.6	183,200
31	64	26.6	189,200
Aug. 1	65	26.6	194,700
2	66	26.6	197,400
3	67	24.4	201,700
4	68	23.3	167,400
5	69	23.3	172,400
6	70	23.8	178,600
7	71	23.8	184,200
8	72	23.8	189,800
9	73	23.8	192,700
10	74	23.8	176,200
11	75	24.4	183,000
12	76	24.4	190,200
13	77	24.4	195,400
14	78	25.5	171,800
15	79	23.3	171,800
16	80	22.2	174,700
17	81	22.2	176,900
18	82	23.3	176,900
19	83	22.2	181,400
20	84	21.1	186,200

Table 19. Data For Ditch 10

May 29 - Oct. 1, 1970 — 126 days

Calendar Day	Ditch Day	Ditch Temperature °C	Characteristics: Volume in Digester Gallons
21	85	21.1	190,000
22	86	20.0	194,600
23	87	21.1	196,400
24	88	21.1	167,400
25	89	21.1	175,700
26	90	22.7	181,300
27	91	23.3	186,300
28	92	21.1	191,200
29	93	21.1	154,500
30	94	21.1	157,900
31	95	20.0	161,700
Sept.1	96	21.1	169,100
2	97	21.1	174,900
3	98	21.1	180,100
4	99	21.1	185,500
5	100	20.2	195,400
6	101	23.8	199,600
7	102	21.1	205,100
8	103	21.1	184,900
9	104	21.1	193,000
10	105	20.0	198,700
11	106	19.4	180,500
12	107	17.7	186,500
13	108	15.5	189,400
14	109	15.5	193,300
15	110	15.5	201,600
16	111	16.6	184,900
17	112	16.6	192,200
18	113	18.3	199,600
19	114	20.0	189,300
20	115	20.1	193,100
21	116	20.1	197,300
22	117	18.3	205,200
23	118	17.7	180,500
24	119	17.7	187,300
25	120	17.7	194,000
26	121	15.5	201,300
27	122	15.5	205,300
28	123	15.5	210,000
29	124	15.5	184,000
30	125	17.7	191,000
Oct. 1	126	17.7	197,600

Table 20. Chemical Oxygen Demand of Supernatant Withdraw From Ditch 10.

Ditch Day	Gallons Removed	COD, ppm
11	35,400	152
16	12,200	98
18	29,700	109
26	44,400	125
34	45,600	270
40	21,600	100
48	48,300	190
52	22,600	300
57	24,600	160
61	22,800	130
68	40,300	166
74	20,000	110
78	23,600	110
88	31,700	
93	44,800	100
103	29,400	140
106	25,900	109
111	27,100	109
114	20,300	150
118	30,900	150
124	34,900	180

Table 21. Data For Ditch 10 - Solids

May 29 - Oct. 1, 1970 — 126 days

Calendar Day	Ditch Day	Ditch Solids			Raw Sludge Solids			
		Total Residue ppm	Volatile Solids ppm	Percent Fixed Solids	Total Residue ppm	Volatile Solids ppm	Percent Fixed Solids	Gallons of Sludge Added
May 29	1	5240	4090	22.0				6100
30	2							2200
31	3				21260	18610	22.5	4800
June 1	4	5960	4580	24.2	13760	11040	19.8	5900
2	5				19480	16690	14.3	5800
3	6	5740	4290	26.3	12670	10640	16.0	8000
4	7				11550	9820	15.0	6300
5	8							5600
6	9							3600
7	10				9140	7380	19.3	3900
8	11	6040	4310	28.6	22190	18350	17.3	6900
9	12				18970	16140	14.9	5100
10	13	7740	5660	26.9	10380	8300	20.0	5900
11	14				15690	12320	21.5	6100
12	15	7770	5300	30.9				5700
13	16							2900
14	17				23200	19160	17.4	4900
15	18				17770	13270	25.3	7000
16	19	9620	7090	26.3	12970	9840	24.1	6100
17	20	8930	6240	30.1	6860	5490	19.9	6300
18	21				9130	6840	25.1	6600
19	22	9615	6330	34.2				6000
20	23							3100
21	24				14970	12280	18.0	3200
22	25	9450	6430	32.0	17650	14010	20.6	6100
23	26				12690			7200
24	27	10860			9840	7910	19.5	6100
25	28				10300	8150	20.8	7200
26	29	10770	7230	31.8				6200
27	30							3400
28	31				7700	6050	21.5	3500
29	32	10450	7240	30.7	15660	12690	18.9	6700
30	33				13150	10730	18.4	5300
July 1	34	12310	8490	31.0	13970	11370	18.6	5400
2	35				13720	10770	21.5	5300
3	36	11860	7640	35.5				5500
4	37							2400
5	38				26010	21490	17.4	3000
6	39	11470	7740	32.5	10060	7950	21.1	8800
7	40				9790	7880	20.5	4600

Table 21. Data For Ditch 10 - Solids

May 29 - Oct. 1, 1970 — 126 days

Calendar Day	Ditch Day	Ditch Solids			Raw Sludge Solids			
		Total Residue ppm	Volatile Solids ppm	Percent Fixed Solids	Total Residue ppm	Volatile Solids ppm	Percent Fixed Solids	Gallons of Sludge Added
8	41	13160	8710	33.8	16510	12880	22.0	6000
9	42				15630	11670	25.3	5300
10	43	13240	8760	33.9				5400
11	44							2100
12	45				16790	13200	21.4	2700
13	46	12770	8180	36.0	16700	13500	19.2	7500
14	47				10740	8380	22.0	5900
15	48	11960	7760	35.1	8900	7030	21.0	7300
16	49				7880	6610	16.1	5800
17	50	13760	9040	34.3				6800
18	51							2700
19	52							4400
20	53	15680	10030	36.0	14280	11220	21.5	5600
21	54				10820	8210	24.1	5700
22	55	12080	9580	36.5	10040	7910	21.2	6400
23	56				11710	8560	26.9	6900
24	57	16170	10280	36.4				7000
25	58							5500
26	59				12140	8690	20.4	4300
27	60	15080	9600	34.3	11570	8550	22.1	7000
28	61							5700
29	62	15170	9590	36.8	15250	12000	21.3	5700
30	63							6000
31	64	15450	9660	37.5				5500
Aug. 1	65							2700
2	66							4300
3	67	14320	9040	36.9				6000
4	68				15150	10950	27.7	5000
5	69	17400	11040	36.6	12540	4900	25.0	6200
6	70				7890	6000	24.0	5600
7	71	16420	10620	35.3				5600
8	72							2900
9	73				10330	7570	32.0	3500
10	74	16070	10250	36.2	12970	10100	22.1	6800
11	75				9260	7430	19.7	7200
12	76	16470	10580	35.8	12130	9120	24.2	5200
13	77	15810	10020	36.4				none
14	78	17560	11140	36.6				none
15	79							2900
16	80				17210	13400	22.1	2200

Table 21. Data For Ditch 10 - Solids

May 29 - Oct. 1, 1970 — 126 days

Calendar Day	Ditch Day	Ditch Solids			Raw Sludge Solids			
		Total Residue ppm	Volatile Solids ppm	Percent Fixed Solids	Total Residue ppm	Volatile Solids ppm	Percent Fixed Solids	Gallons of Sludge Added
17	81	17010	10740	36.9				none
18	82							4500
19	83				13420	10490	21.8	4800
20	84	15850	9940	37.3	12810	10550	17.6	3800
21	85	15770	9850	37.5				4600
22	86							1800
23	87				13990	11340	19.0	2700
24	88	14700	9280	36.9	15480	11130	28.1	8300
25	89	17680	11190	36.7	11310	9480	16.2	5600
26	90				8320	6410	23.0	5000
27	91	16920	10770	36.4	12320	9780	20.6	4900
28	92	19790	12630	36.2				8100
29	93							3400
30	94	18110	11750	35.1	16020	12840	19.8	3800
31	95							7400
Sept.1	96	18550	11990	35.4	4740	3550	25.1	5800
2	97	17900	11440	36.1	5870	4460	24.0	5200
3	98				14900	11700	21.5	5400
4	99	16990	10780	36.6				9900
5	100							4200
6	101							5500
7	102				24350	17750	27.1	9200
8	103	18390	12070	34.4	16060	12450	22.5	8100
9	104				12120	9740	19.6	5700
10	105				14810	11730	20.8	7700
11	106	19440	12520	35.6				6000
12	107							2900
13	108				15670	12900	17.7	3900
14	109	18290	11890	35.0	17250	13860	19.7	8300
15	110				17450	13310	23.7	10400
16	111				10390	7710	25.8	7300
17	112	19550	13240	32.3				7400
18	113							10000
19	114							3800
20	115				17130	14250	16.8	4200
21	116	19810	13460	32.1				7900
22	117				13170	10360	21.3	6200
23	118	21840	14860	32.0	17260	14230	17.6	6800
24	119				11010	9300	15.5	6700
25	120	20400	14140	30.7				7300

Table 21. Data For Ditch 10 - Solids

May 29 - Oct. 1, 1970 — 126 days

Calendar Day	Ditch Day	Ditch Solids			Raw Sludge Solids			
		Total Residue ppm	Volatile Solids ppm	Percent Fixed Solids	Total Residue ppm	Volatile Solids ppm	Percent Fixed Solids	Gallons of Sludge Added
26	121							4000
27	122				16070	13400	16.6	4700
28	123				20900	16850	19.4	8900
29	124	22640	15620	30.0	15920	13070	17.9	7000
30	125	21990	15260	30.6	14500	11980	17.4	6600
Oct. 1	126	21120	14590	30.9				none

Table 22. Data For Ditch 10 - COD and Phosphorus

May 29 - Oct. 1, 1970 — 126 days

Calendar Day	Ditch Day	COD			Phosphorus		
					Phosphate	Total Phosphorus	
		Effluent ppm	Raw Sludge ppm	Ditch Compos. ppm	Effluent ppm	Raw Sludge ppm	Ditch Compos. ppm
May 29	1						
30	2		35800				
31	3	150		5400			
June 1	4		16400				
2	5		28290				
3	6	130	12090	5990	8		
4	7	150	17800	5570			
5	8						
6	9						
7	10		12620				
8	11	57	30000	4900	11		
9	12		30960				
10	13	200	12210	7440			
11	14		14070				
12	15	98		6300	19		
13	16						
14	17		35290				
15	18		18510				
16	19	110	14340	3970			
17	20	170	9380	7130	61		
18	21		8270				
19	22	110		6240	50	450	
20	23						
21	24		18540				
22	25	110	18350	7620	56	500	
23	26		18380			650	
24	27	120	10900	7690	52		
25	28		10540			360	
26	29	130		7080	39		
27	30					150	
28	31		7530		52		
29	32		18540	6440			
30	33		13700				
July 1	34	120		8690	49		
2	35		14110			750	
3	36	200		8830	50		
4	37						
5	38		27080				
6	39	270	10440	7320	76		
7	40		15150			760	

Table 22. Data For Ditch 10 - COD and Phosphorus

May 29 - Oct. 1, 1970 — 126 days

Calendar Day	Ditch Day	COD			Phosphorus		
					Phosphate	Total Phosphorus	
		Effluent ppm	Raw Sludge ppm	Ditch Compos. ppm	Effluent ppm	Raw Sludge ppm	Ditch Compos. ppm
8	41	160	16920	10080	71		
9	42		19770	9110		780	
10	43	170		11330	90		
11	44						
12	45		16880			770	
13	46	100	19500	8700	90		
14	47		12850				
15	48	290	21030	8560	104		
16	49		19680			770	
17	50	190		10340	84		
18	51						
19	52						
20	53	200	31470	11720	75		
21	54		12750			1050	
22	55	300	12500	10640	65		
23	56		13480			870	
24	57	160		12470	65		
25	58						
26	59		11630			460	
27	60	160	14570	10350	60		500
28	61						
29	62	170		10350	66		
30	63		18260				
31	64	120		11460	66		
Aug. 1	65		25070				
2	66	130	13290				
3	67		14680	10760	62		
4	68	200	17020			1440	
5	69		10320	13460	54		1030
6	70	50	10320				
7	71			13110			
8	72						
9	73		12230				
10	74	130	15970	12690	56		1030
11	75		12470			720	
12	76	110		11660	86		
13	77						
14	78			14630			
15	79						
16	80		20680			1040	

Table 22. Data For Ditch 10 - COD and Phosphorus

May 29 - Oct. 1, 1970 — 126 days

Calendar Day	Ditch Day	COD			Phosphorus		
					Phosphate	Total Phosphorus	
		Effluent ppm	Raw Sludge ppm	Ditch Compos. ppm	Effluent ppm	Raw Sludge ppm	Ditch Compos. ppm
17	81	130		13110	86		1920
18	82		12320			940	
19	83	190	13430	11720	95	1712	
20	84	120	15350	14920			
21	85			12780	100	560	1200
22	86						
23	87		15690				
24	88	110	15440	11450	69	370	1040
25	89	110	15630	14130			
26	90	110	10520	14780	97		
27	91	100	16490	14370			1220
28	92			13240	120	400	
29	93			16000	95		1200
30	94		18390			980	
31	95	120		15140	90		1600
Sept.1	96		8110	14280		610	
2	97	140	8370	14450	92		2130
3	98		20410	14180			
4	99			14430	75		1920
5	100						
6	101						
7	102		21360				
8	103		17640	16070	67	544	3380
9	104	110	15560				
10	105		19090				1310
11	106			17820	73	500	
12	107						
13	108		19820			560	
14	109		20510	17270	65		1390
15	110		20260				
16	111		13410			480	
17	112	150		17280	70		1220
18	113						
19	114						
20	115					690	
21	116			17860	76		1520
22	117		15260			740	
23	118	80	21630	19200	48		1540
24	119	180	35390	20380		450	
25	120			19620	46		1260

Table 22. Data For Ditch 10 - COD and Phosphorus

May 29 - Oct. 1, 1970 — 126 days

Calendar Day	Ditch Day	COD			Phosphorus		
					Phosphate	Total Phosphorus	
		Effluent ppm	Raw Sludge ppm	Ditch Compos. ppm	Effluent ppm	Raw Sludge ppm	Ditch Compos. ppm
26	121						
27	122		20820				
28	123		25540			860	
29	124	170	17960	22100	46	590	1780
30	125	80	18930	21360	61		1640
Oct. 1	126	190		20090			

Table 23. Data For Ditch 10 - Nitrogen

May 29 - Oct. 1, 1970 — 126 days

Calendar Day	Ditch Day	Nitrogen					
		Ammonia		Organic Nitrogen			Nitrate
		Raw Sludge ppm	Effluent ppm	Raw Sludge ppm	Effluent ppm	Ditch Compos. ppm	Effluent ppm
May 29	1						
30	2						
31	3	72		380			
June 1	4		1.5		8.4		
2	5	30		380			
3	6	24	0.5	140	9.2		
4	7						
5	8						
6	9						
7	10	28		180			
8	11	48	1.6	460	4.5		2.8
9	12	56		280			
10	13	30	1.7	240	5.0		2.2
11	14	37		460			
12	15		1.2		6.0		3.2
13	16						
14	17						2.0
15	18						
16	19	86		560			
17	20	76	5.0	360	5.5		
18	21	68		400			2.0
19	22		0.3		4.9		4.8
20	23						
21	24						
22	25	140		360			
23	26	56	1.5	360	5.0		5.1
24	27	24	2.0	400	3.7		
25	28	46	1.8	260	3.1	220	
26	29		0.6		4.0		
27	30						
28	31	40		320			6.2
29	32		2.3		5.7		
30	33	72		390			
July 1	34	56	none	370	7.5		4.9
2	35	44	2.6	410	5.6		
3	36		none		6.3		6.4
4	37						
5	38	134		1070			
6	39	64	2.0	360	3.5	460	8.5
7	40	50		180			

Table 23. Data For Ditch 10 - Nitrogen

May 29 - Oct. 1, 1970 — 126 days

Calendar Day	Ditch Day	Nitrogen					
		Ammonia		Organic Nitrogen			Nitrate
		Raw Sludge ppm	Effluent ppm	Raw Sludge ppm	Effluent ppm	Ditch Compos. ppm	Effluent ppm
8	41	66	4.0	410	3.1	480	9.3
9	42	41		300			
10	43		2.5		5.5	480	16.3
11	44			530			
12	45	72		620			
13	46	82	1.4	560	4.0	210	26.1
14	47	60	2.3	480	6.7	360	
15	48	55		450		290	30.1
16	49	23					22.1
17	50		1.1		5.3		18.1
18	51						
19	52						
20	53	34	0.5	440	2.3	200	17.3
21	54	48	none	320	2.8	290	16.0
22	55	37	1.0	200	4.5	350	14.1
23	56	56		600		230	
24	57		0.8		6.1	420	7.0
25	58						
26	59	60		240			
27	60	56	0.8	220	7.8	600	14.7
28	61					440	
29	62	40	none	370	3.9	590	7.2
30	63		0.5		4.3	630	6.5
31	64						
Aug. 1	65						
2	66						
3	67	6[illegible]	0.9	220	4.5	310	8.7
4	68	30		400			
5	69	28	0.5	560	10.0	550	4.2
6	70	38		400			
7	71	34	1.4	320	8.3	530	1.1
8	72						
9	73						
10	74	34	1.5	170	12.3	730	0.9
11	75	40		600			
12	76	24	0.9	200	8.0	630	0.6
13	77	32		430		580	
14	78						
15	79						
16	80						16.5

Table 23. Data For Ditch 10 - Nitrogen

May 29 - Oct. 1, 1970 — 126 days

Calendar Day	Ditch Day	Nitrogen					
		Ammonia		Organic Nitrogen			Nitrate
		Raw Sludge ppm	Effluent ppm	Raw Sludge ppm	Effluent ppm	Ditch Compos. ppm	Effluent ppm
17	81						
18	82	31		290			
19	83		0.6		5.8	460	22.3
20	84	55		200			29.7
21	85		1.0		3.7	250	
22	86						
23	87						
24	88						
25	89	83		930			18.8
26	90	44	1.3	380	7.2	750	
27	91		1.3		4.6		
28	92		1.8		5.2	680	
29	93						
30	94	120		330			
31	95					200	14.6
Sept.1	96		none		5.2		
2	97	28	none	360			10.2
3	98		1.1		6.0	700	
4	99	64		240			8.4
5	100		none		5.0	570	
6	101						
7	102	90	none	610	14.0		
8	103					540	none
9	104						none
10	105	56		850			
11	106		none		23.0	670	none
12	107						
13	108	74		360			
14	109		none		4.8	290	0.5
15	110						
16	111	44					
17	112		none	460			none
18	113						
19	114						
20	115	76		970			
21	116		none			870	none
22	117	66		210			
23	118	78	none	330	4.7	500	none
24	119	47	none	370	7.5	900	
25	120		none		3.5	520	none

Table 23. Data For Ditch 10 - Nitrogen

May 29 - Oct. 1, 1970 — 126 days

Calendar Day	Ditch Day	Nitrogen					
		Ammonia		Organic Nitrogen			Nitrate
		Raw Sludge ppm	Effluent ppm	Raw Sludge ppm	Effluent ppm	Ditch Compos. ppm	Effluent ppm
26	121						
27	122						
28	123	85	none	380	4.3	490	
29	124						none
30	125						
Oct. 1	126						none

APPENDIX B

Table 24. Data For Ditch 11

Oct. 26 - Nov. 23, 1970 — 29 days

Calendar Day	Ditch Day	Characteristics	
		Temperature °C	Volume of Digester Gallons
Oct. 26	1	17.7	
27	2	16.6	198,000
28	3	15.5	202,300
29	4	14.4	180,500
30	5	13.6	187,100
31	6	11.1	189,300
Nov. 1	7	11.1	193,600
2	8	11.1	198,000
3	9	11.1	202,300
4	10	10.0	184,900
5	11	11.1	191,500
6	12	11.4	198,000
7	13	13.9	182,700
8	14	13.9	189,300
9	15	12.7	193,600
10	16	12.7	202,300
11	17	12.8	211,100
12	18	12.7	215,400
13	19	11.6	182,700
14	20	10.5	181,100
15	21	10.0	189,300
16	22	10.0	193,600
17	23	12.7	202,300
18	24	12.7	184,900
19	25	11.1	193,600
20	26	11.1	206,700
21	27	11.1	193,600
22	28	8.8	200,200
23	29		204,500

Table 25. Data For Ditch 11 - Solids

Oct. 26 - Nov. 23, 1970 — 29 Days

Calendar Day	Ditch Day	Solids						
		Ditch Solids			Raw Sludge			
		Total Residue ppm	Volatile Solids ppm	Percent Fixed Solids	Total Residue ppm	Volatile Solids ppm	Percent Fixed Solids	Gallons of Sludge Added
Oct. 26	1	12910	8790	32.0	23490	19700	16.1	5700
27	2	12860	8780	31.7				6200
28	3							8300
29	4				10720	8960	16.5	6400
30	5	13430	9160	31.8				5800
31	6							3700
Nov. 1	7				15210	12000	21.1	4100
2	8	13250	8840	33.3				8200
3	9				18920	15250	19.4	9600
4	10	15910	11230	29.4	13480	11320	16.0	6400
5	11	14870	10400	30.1	15370	12910	16.0	7000
6	12	16140	11460	29.0				4900
7	13							5800
8	14				32920	27160	47.8	3800
9	15	16140	11290	30.0	17200	14190	17.5	9600
10	16	16100	11520	28.4	16100	11520	28.5	7600
11	17	15990	11390	28.8	15990	13140	17.8	7200
12	18				12480	10090	19.2	9500
13	19	18150	13140	27.6				6600
14	20							4400
15	21				18300	15240	16.7	4000
16	22	16850	12210	27.5	18460			9100
17	23				15270	11650	25.7	12200
18	24	18630	13390	28.1	14400	12080	16.1	8300
19	25				12920	10750	16.8	6500
20	26							7300
21	27							5400
22	28				12160	10100	16.9	4900
23	29	18230	13430	26.3				7300

Table 26. Data For Ditch 11 - COD and Phosphorus

Oct. 26 - Nov. 23, 1970 — 29 days

Calendar Day		Ditch Day	COD			Phosphate	Total Phosphorus	
			Effluent ppm	Ditch Compos. ppm	Raw Sludge ppm	Effluent ppm	Raw Sludge ppm	Ditch Compos. ppm
Oct.	26	1	80	11630	33990	41		730
	27	2	80	11140		46	690	780
	28	3						
	29	4			14260			
	30	5	90	12040		47		
	31	6						
Nov.	1	7			19090			
	2	8	75	12180		46		
	3	9						
	4	10			21010			
	5	11	92	15030	23580	46	1010	
	6	12	100	15340		41		
	7	13						
	8	14			39560			
	9	15	90	14990	24170		910	
	10	16		14580	23790			
	11	17		15750	20860		640	
	12	18	82		16830	32		
	13	19		17860				
	14	20						
	15	21			24180			
	16	22		17040	27290		670	
	17	23	125		17890			
	18	24			23450		740	
	19	25		18660	17710			
	20	26	180			30	530	
	21	27						
	22	28			16110			
	23	29		18090		31	640	1010

Table 27. Data For Ditch 11 - Nitrogen

Oct. 26 - Nov. 23, 1970 — 29 days

Calendar Day	Ditch Day	Nitrogen					
		Ammonia		Organic Nitrogen			Nitrate
		Raw Sludge ppm	Effluent ppm	Raw Sludge ppm	Effluent ppm	Ditch Compos. ppm	Effluent ppm
Oct. 26	1	102	none	560	3.5	310	0.9
27	2		none		4.8	410	1.2
28	3						
29	4	55		420			
30	5		none		5.0	640	none
31	6						
Nov. 1	7						
2	8		none		3.0	570	1.4
3	9						
4	10	40		550			
5	11	65	none	560		600	none
6	12		none		2.5	560	none
7	13						
8	14	130		930			
9	15	100	.8	670	2.5	550	none
10	16						
11	17	64		690			none
12	18	43		610	3.4		
13	19					760	
14	20						
15	21						
16	22	54		630			
17	23		none		6.1		
18	24	66		440			none
19	25	59	none	500		640	
20	26		none		8.4		none
21	27						
22	28	75	0.5	470	6.1	720	
23	29						

APPENDIX C

Table 28. Data For Ditch 12

Jan. 6 - Jan. 29, 1971 — 23 days

Calendar Day	Ditch Day	Characteristics	
		Temperature ^{o}C	Volume of Digester Gallons
Jan. 6	1	11.1	176,200
7	2	9.4	180,500
8	3	8.8	187,100
9	4	8.8	198,000
10	5	7.7	200,200
11	6	8.8	204,500
12	7	8.8	211,100
13	8	8.8	182,700
14	9	9.4	189,300
15	10	8.8	191,500
16	11	8.8	193,600
17	12	8.3	200,200
18	13	7.2	204,500
19	14	8.8	213,300
20	15	6.7	174,000
21	16	8.8	184,900
22	17	10.0	189,300
23	18	10.0	193,600
24	19	9.9	200,200
25	20	9.9	202,300
26	21	9.9	206,700
27	22	10.0	180,500
28	23	8.8	184,900
29	24	8.8	191,500

Table 29. Data For Ditch 12 - Solids

Jan. 6 - Jan. 29, 1971 — 23 days

Calendar Day	Ditch Day	Solids						
		Ditch Solids			Raw Sludge			
		Total Residue ppm	Volatile Solids ppm	Percent Fixed Solids	Total Residue ppm	Volatile Solids ppm	Percent Fixed Solids	Gallons Sludge Pumped
Jan. 6	1	4930	3420	30.7	11130	9690	12.9	7100
7	2				13290	11080	16.7	6500
8	3	5960	4350	27.0				8500
9	4							3300
10	5				20570	16800	18.3	5700
11	6	6570	4870	27.8	16030	13240	17.4	6700
12	7				11250	9270	17.6	6200
13	8	8640	6340	26.6	14440	12120	16.1	7000
14	9							3400
15	10							6400
16	11							4200
17	12				22330	18210	18.5	4500
18	13	9790	7050	27.9	16580	13850	16.5	11400
19	14				16340	12720	22.2	6800
20	15	11900	8500	28.6	12700	10590	16.6	7200
21	16				14050	11400	18.8	6700
22	17	12130	8950	26.2				6500
23	18							3600
24	19				15130	12610	16.7	3800
25	20	10780	7870	27.0	16780	14090	26.3	7800
26	21				15110	11760	22.2	9600
27	22	13310	9900	25.6	7160	5890	17.7	6900
28	23				15810	13070	17.3	6500
29	24	12070	8830	26.8				

Table 30. Data For Ditch 12 - COD and Phosphorus

Jan. 6 - Jan. 29, 1971 — 23 days

Calendar Day	Ditch Day	COD			Phosphorus		
					Phosphate	Total Phosphorus	
		Effluent ppm	Ditch Compos. ppm	Raw Sludge ppm	Effluent ppm	Ditch Compos. ppm	Raw Sludge ppm
Jan. 6	1	100	9210		34		
7	2						1070
8	3				23		370
9	4						
10	5			24870			
11	6	84	6410	19350			
12	7			13200			
13	8	75	7720	19910			
14	9						
15	10						
16	11						
17	12			26130			
18	13		9320	22590			
19	14	142		21520	18		
20	15		12210	17890			670
21	16			18640			
22	17		12960				540
23	18						
24	19			19600			
25	20		10800	20740			
26	21	370		19720	30		
27	22		13090	12170			
28	23			19760			
29	24		12840				

Table 31. Data For Ditch 12 - Nitrogen

Jan. 6 - Jan. 29, 1971

Calendar Day	Ditch Day	Nitrogen					
		Ammonia		Organic Nitrogen			Nitrate
		Effluent ppm	Raw Sludge ppm	Effluent ppm	Ditch Compos. ppm	Raw Sludge ppm	Effluent ppm
Jan. 6	1	3.5		1.7	120		
7	2						
8	3						3.4
9	4						
10	5		74			470	
11	6	0.8		2.0	230		
12	7	1.1	51	1.5		400	2.3
13	8		52			940	1.9
14	9						
15	10						
16	11						
17	12		79			400	
18	13		45		350	330	none
19	14	1.2	55	3.3		450	none
20	15		48			290	none
21	16		53			400	
22	17	0.5		2.6	310		none
23	18						
24	19		65			350	
25	20				470		none
26	21		48	8.4		610	none
27	22				480		
28	23						
29	24						none

APPENDIX D

EXPERIMENTAL

The several problems occurring during the operation of the aeration channel made it difficult to accurately evaluate the efficiency of the process. In order to understand the capabilities and basic fundamentals of the process more fully, various "in-laboratory" studies were undertaken. These experiments were involved with the performance of a small batch unit digester under controlled conditions of temperature, DO and sludge addition.

The apparatus (Figure 1) for the digester consisted of a battery jar filled with eleven liters of tap water and one liter of activated sludge collected from the River Falls waste treatment plant. In order to keep the solids in suspension, an electric stirring motor with stainless steel propeller was used. Two gas diffusion tubes placed opposite one another, provided additional agitation as well as aeration. A small air compressor operated continuously (output of 1200 cc. air/min.) for the duration of the experiments. To study the effect of sludge additions on the dissolved oxygen concentration of the mixed liquor, a Weston Stack Model 3008 DO meter and recorder assembly was used.

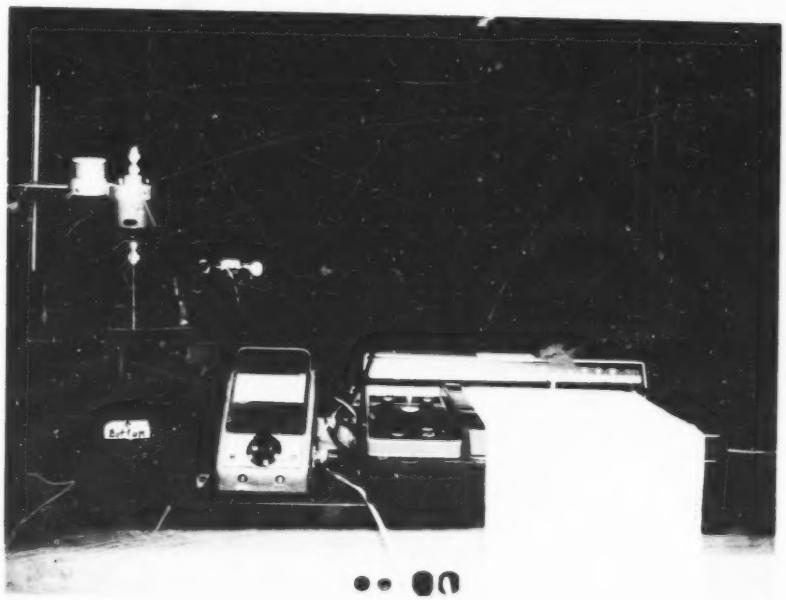

Figure 1. In-lab Digester and Recorder

Three separate experiments, designated Units 1, 2 and 3, were accomplished using the battery jar digesters. The experimental temperatures of operation were respectively 25°, 24°, and 10°C for Units 1, 2 and 3. The oxygen diffusion probe and recorder assembly was used in Unit 2 to acquire a continuous record of the DO before and after sludge addition. For Units 1 and 3, 400 mls of digester contents were removed each day for analysis and replaced with 400 mls of freshly collected raw sludge. The volumes used were comparable to additions of sludge to the channel at the waste treatment plant. Any water lost due to evaporation was replaced before removing the sample. The sides and bottom of the battery jar were scraped free of any residue accumulation before sampling. Digester number 2 also received 400 mls of raw sludge daily, however, the sludge was added in 100 ml portions at two-hour intervals. This method of addition enabled the investigators to determine whether small or large batch additions were most effective. Facilities did not permit the operation of more than one batch unit at a time, hence the daily difference in the raw sludge added was an obvious, but unavoidable variable in these experiments.

In each of the three test units, two types of bacterial time studies were performed. The first study consisted of studying the effects of unsterilized raw sludge additions on the total number of bacteria present. Four plates (Standard Plate Count Method) were made from serially diluted samples taken from the digester immediately prior to sludge addition and at 2, 4, 6, 8, and 10 hours after sludge addition. For Unit 2, the study commenced following the final 100 ml addition of raw sludge on the day indicated. The second study examined the effects of sterilized raw sludge addition on the total number of bacteria present. Total bacterial number was again determined before sludge addition and at regular intervals after sludge addition.

The parameter used to describe efficiency in these studies was volatile solids reduction. The volatile solids content of the raw sludge added and the digester contents removed was determined daily. The efficiency of the process was calculated as previously described.

APPENDIX D

DISCUSSION

The daily dissolved oxygen data for Units 1, 2 and 3 appear in Table 1. The values reported represent only the dissolved oxygen (DO) content of the respective batch units just prior to the addition of raw sludge. In the case of batch Unit 2, the listed value is the DO concentration prior to the first addition of raw sludge on the day indicated. The overall average DO concentration is indicated for each batch unit and a 12-day average for Units 1 and 3 has been included for purposes of comparison with Unit 2.

The DO content of the mixed liquor for Units 1 and 2 during the 12-day comparison period was essentially the same (6.8 and 6.7 ppm respectively). It is of interest to note that all units experienced a distinct decline in DO concentration as digester contents aged. This suggests that an increasing oxygen demand parallels accumulation of solid material and/or that the solubility of oxygen decreases as insoluble solids and salt content increases. The increased solids content should support a greater population of bacteria, which would result in a higher oxygen requirement. Table 2 shows that the total bacterial population, for all units did increase with time.

There was no evidence to suggest that oxygen was even slightly limiting in batch Unit 3 (low temperature study), however the trend of gradually decreasing DO concentrations also occurred. The DO content remained consistently higher than for either of the other two units (Table 1). The higher DO content of Unit 3, indicates a much lower biological oxygen requirement.

As previously mentioned, the data appearing in Table 1 do not reflect the DO content of the mixed liquor shortly after sludge addition. Tables 3, 4 and 5 provide information which demonstrates the effect of raw sludge addition on the DO concentrations. The organisms present in the raw sludge added and those already present in the digester (activated sludge organisms) were primarily responsible for the oxygen demand. In order to identify the extent of each, an experiment was performed in which either unsterilized (Table 3) or sterilized (Table 4) raw sludge additions were made. The oxygen demand resulting from the addition of sterile raw sludge additions was believed to be primarily effected by activated sludge organisms. It is understood that other possible influences on DO content include a chemical oxygen demand, decreasing solubility of oxygen with increasing salt concentration, and dilution by addition of oxygen-free raw sludge.

Table 3 shows that a sharp decrease in DO occurs after the addition of unsterilized raw sludge. It is of interest to note that the time required to reach the minimum DO becomes less for each succeeding addition. Although supporting data were unavailable there does appear to be some indication that the response of the organisms to sludge addition appeared

Table 1. Daily Dissolved Oxygen Levels (ppm)[1]

Day of Operation	Unit 1 400 ml additions	Unit 2 100 ml additions	Unit 3 400 ml additions
0[2]	8.6	8.3	10.6
1	8.4	7.8	-
2	7.7	7.7	-
3	7.3	7.4	10.2
4	6.9	7.0	9.8
5	6.4	6.8	9.5
6	-	7.1	-
7	6.7	6.5	-
8	7.2	-	9.7
9	6.4	-	9.3
10	-	6.1	-
11	5.7	5.6	8.9
12	5.3	5.2	9.2
13	4.9	-	-
14	4.9	-	9.0
15	5.4	-	9.0
16	4.7	-	-
17	-	-	-
18	-	-	-
19	3.8	-	9.5
20	4.3	-	8.6
21	4.5	-	-
22	4.0	-	9.4
23	-	-	8.4
24	-	-	-
25	-	-	-
26	-	-	7.9
12 day Average	6.8	6.7	9.5
Overall Average	5.8	6.7	9.2

1-Reported DO values all taken before the addition of Raw Sludge.

2-Day 0 is not included in the average DO value as no raw sludge had yet been added.

Table 2. Daily Total Bacterial Population Counts (millions/ml)

Day of Operation	Unit 1 400 ml additions	Unit 2 100 ml additions	Unit 3 400 ml additions
0	-	-	-
1	3.4	-	0.8
2	4.1	-	-
3	-	4.0	-
4	5.7	6.4	1.1
5	-	9.3	2.5
6	6.3	-	-
7	5.9	11.3	-
8	7.7	10.7	3.7
9	-	-	4.2
10	12.2	14.7	5.1
11	9.8	15.9	-
12	-	16.4	-
13	-	-	7.4
14	11.7	-	8.2
15	14.3	-	9.5
16	13.8	-	-
17	-	-	11.6
18	10.5	-	-
19	-	-	8.5
20	14.6	-	7.6
21	16.1	-	9.1
22	15.5	-	8.7
23	-	-	-
24	-	-	-
25	-	-	10.4
26	-	-	10.5
Average	10.1	11.9	6.8

Table 3. Unit 2 Time Study Dissolved Oxygen (ppm) Data

(400 mls Unsterilized Raw Sludge[1] added in 100 mls portions)

Addition Number	Dissolved Oxygen Initial[2]	Dissolved Oxygen Minimum[3]	DO[4]	T_1[5] Minutes	Final DO[6]	T_2[7] Minutes
1	6.5	2.2	-4.3	20	6.8	74
2	7.3	2.7	-4.6	18	6.5	75
3	7.0	2.2	-4.8	16	6.3	65
4	6.0	1.4	-4.6	15	5.1	72

1-Sludge data - Total residue 12130 mg/l
Volatile residue 9920 mg/l

2-Dissolved Oxygen initital - DO concentration prior to raw sludge addition

3-Dissolved Oxygen minimum - DO concentration at its lowest point after sludge addition

4-DO - The numerical difference between initial and minimum DO concentration

5-T_1 - Time in minutes necessary to attain minimum DO

6-Final DO - The Dissolved Oxygen concentration when DO plateau is reached

Table 4. Unit 2 Time Study Dissolved Oxygen (ppm) Data[1]

(400 mls Sterilized Raw Sludge[1] added in 100 mls portions)

Addition Number	Dissolved Oxygen Initial[2]	Dissolved Oxygen Minimum[3]	DO[4]	T_1[5] Minutes	Final DO[6]	T_2[7] Minutes
1	5.6	3.8	-1.8	15	5.0	56
2	5.1	3.1	-2.0	16	4.5	61
3	4.7	2.5	-2.2	13	4.2	67
4	4.2	1.8	-2.4	14	3.8	55

See Legend - Table 3

to improve with each successive 2 hour addition. The system recovered slowly, as indicated by an increasing DO content of the mixed liquor. The end of this recovery phase was marked by the onset of a DO plateau. This plateau was arbitrarily defined as a change in DO content of less than 0.1 ppm in a 10 minute interval.

Table 5. Unit 1 Time Study Dissolved Oxygen (ppm) Data[1]

(400 mls Unsterilized Raw Sludge added in a single addition)

Day 8[2]		Day 20[3]	
Time (hrs.)	DO ppm	Time (hrs.)	DO ppm
0.0	7.2	0.0	4.3
0.5	0.2	0.5	0.4
1.0	0.5	1.0	0.7
2.0	1.9	1.5	1.1
3.0	4.6	2.0	1.4
24.0	6.4	2.5	1.5
		24.0	4.5

1-This data was obtained by spot checking with portable DO meter at the indicated Time intervals after Raw Sludge addition

2-Day 8; total residue 17400, volatile residue 14790

3-Day 20; total residue 13641; volatile residue 11370

The DO deflection was significantly less (Table 4) when sterilized raw sludge was used. The data indicates that the DO plateau of the mixed liquor was attained in less time following the addition of sterile sludge, as compared to unsterilized sludge. The DO decrease was less abrupt and the average values for T_1 and T_2 were lower. The volatile residues of the raw sludge added were shown by analyses to be approximately the same (Legend, Tables 3 and 4). This is not, however, to imply that the two raw sludge samples were identical, but it does indicate that in regard to the parameter (volatile residue) examined both samples were almost identical.

In summary, it is felt that the large and immediate drop in DO, as a result of raw sludge addition, is not exclusively due to an immediate population increase in the activated sludge organisms. Experiments with unsterile and sterile raw sludge revealed that the immediate population increase in the batch unit was the result of the organisms present in the raw sludge. There is no other plausible explanation for the large observed difference in DO following addition of sterile versus unsterile raw sludge. These studies also imply that there is a significant amount of readily available food material in raw sludge

which can be assimilated almost instantaneously by the activated sludge organisms. The initial DO drop is believed to be due to a biological oxygen requirement of the bacteria present. The addition of a readily available food source apparently stimulates the metabolic activities of the bacteria. This contention is supported by studies with sterile raw sludge (Table 4).

The large DO values observed following addition of raw sludge to the batch units were interpreted as shock loading. Pipes[1,2] defined a shock load as any sudden change in the concentration, composition or flow rate of the waste received. This situation leads to decreased efficiency of an aerobic system. In the present investigation the shock loading effects of adding 100 or 400 ml portion of unsterilized raw sludge can be seen in Tables 3 and 5. Wuhrmann[3] has calculated that if the mixed liquor DO concentration is 2.0 ppm, the centermost organisms of a 500 micron diameter floc particle will be respiring at an oxygen concentration of 0.1 ppm. Hence, a considerable number of the floc organisms will not have their oxygen requirement met and a large percentage of the cells in the floc particle will be of little use. A function of the floc particle is to provide organisms with an adsorptive surface onto which insoluble materials may physically collect. This affords the floc-forming organisms the opportunity to hydrolyze complex substances to simpler compounds before assimilation. Wuhrmann suggests that a sudden drop in DO concentration (shock loading) could effectively break up the floc particles.

It is assumed that the environmental conditions in the digester determine the populations of microorganisms present and the physical form of their associations.[2] Thus, environmental conditions (pH, temperature, DO) influence the type of sludge produced. Pipes stated that at low DO concentrations the filamentous form, is predominant. The disadvantage of filamentous forms is that they are unable to effectively handle complex or insoluble substances. The result, of course, is a markedly less efficient process. If, as Wuhrmann contends, low oxygen concentrations retard floc development or destroy floc particles and favor filamentous forms, then large additions of raw sludge and the low oxygen conditions they effect should be avoided.

The daily total bacterial population of Units 1, 2 and 3 are indicated in Table 2. The total bacterial population was determined prior to raw sludge addition. The DO concentration was also determined at this time. For Unit 2, the sampling was performed immediately before the initial 100 ml addition of raw sludge. Table 2 shows a trend toward increasing population size in all units with respect to time.

In the discussion section of this report the concept of "maturation phase" was introduced. This was described as the period of time required for aging of the digester contents before satisfactory process efficiency was attained. The bacterial population during this phase was observed to increase steadily. Further, any environmental factor (DO, temperature, etc.) could effectively lengthen or shorten the time necessary for maturation of the activated sludge. Some insight into the mechanics of this maturing

phase has been provided by Brock.[4] He contended that the adsorption of the cells and nutrients to surfaces of particulate matter increased the cells' ability for growth beyond what was possible in a free suspension. Presumably, this id due to an inability of the organisms to concentrate nutrients in a suspension. Heukelekian and Heller[5] demonstrated a marked increase in growth of Escherichia coli simply by introducing glass beads into the culture media. These studies suggest that the addition of solid material (inorganic or organic) will effect an increase in population by providing greater adsorptive surface area for microbial activity. Hence the efficiency of the system will approach a maximum value as the solids content increases.

Although all batch units showed a definite trend for increasing population, smaller more frequent additions of raw sludge resulted in substantially larger bacterial populations (Table 2). Stabilization of volatile solids was also noted to be more complete under these circumstances (Table 10). Low temperature (10°C) was undoubtedly a major deterrent to activity in Unit 3. However, temperature cannot account for the differences observed between Units 1 and 2. The average temperature of operation was essentially the same, 25°C and 24°C respectively for Units 1 and 2. The only difference was the method of sludge addition and corresponding oxygen demand created. Unit 1 experienced a shock loading similar to that occurring in the aeration channel. In contrast, shock loading in Unit 2 was less drastic; the total oxygen demand was exerted over a longer period of time. It was previously mentioned that environmental conditions will control the types and number of microorganisms present.[2] Wuhrmann determined that a low DO concentration could retard bacterial activity by creating conditions unfavorable for floc formation.[3] During this investigation residual DO is essentially the same for both units. Apparently, shock loading was responsible for the reduced bacterial population found in Unit 1.

One other consideration which should not be overlooked is the strength and nature of the raw sludge added. In terms of volatile solids, the strength of the raw sludge added to Unit 1 was significantly higher. During the 12-day comparison period, the average volatile solids content added to Unit 1 was 5400 ppm higher than that added to Unit 2. Hence, one would have expected a higher bacterial population in Unit 1 because of the greater availability of food. However, the DO present after sludge addition was apparently inadequate to meet the bacterial requirement, hence the smaller observed populations (Table 2).

For each batch unit, addition of non-sterile raw sludge effected an immediate increase in bacterial numbers in all units. In every case, the largest single increase was realized during the first 2 hours after sludge addition. The increase for Unit 2, however, was markedly less than either of the other units (Tables 6, 7 and 8). This is not unexpected as smaller quantities of raw sludge will contain fewer bacteria and less food material. In part, the total population attained is somewhat dependent on the available organic food materials.

Table 6. Unit 1 Time Study Population Change (millions/ml)

(400 mls sludge added in a single addition)

Hours After Sludge Addition	Temp. 25°C. Non-Sterile (day 7)	Change in Population	Sterile (day 15)	Change in Population
0	5.9		14.3	
2	9.4	+3.5	14.9	+0.6
4	10.7	+1.3	16.1	+1.2
6	9.3	-1.4	16.9	+0.8
8	8.4	-0.9	16.8	-0.1
24	7.7	-0.7	13.8	-3.0
Overall Population Change	+1.8		-0.5	

Table 7. Unit 2 Time Study Population Change (millions/ml)

(400 mls sludge added in a single addition)

Hours After Sludge Addition	Temp. 24°C. Non-Sterile (day 7)	Change in Population	Sterile (day 15)	Change in Population
0	10.3	-	15.9	-
2	12.0	+1.7	16.1	+0.2
4	12.9	+0.9	16.6	+0.5
6	13.6	+0.7	17.3	+0.7
8	14.2	+0.6	17.0	-0.3
10	-	-	17.1	+0.1
24	10.7	-3.5	16.4	-0.7
Overall Population Change	+0.4		+0.5	

Table 8. Unit 3 Time Study Population Change (millions/ml)

(400 mls of sludge added in a single addition)

Hours After Sludge Addition	Temp. 10°C. Non-Sterile (day 14)	Change in Population	Sterile (day 19)	Change in Population
0	8.2		8.5	
2	10.6	+2.4	8.6	+0.1
4	10.5	-0.1	8.2	-0.4
6	9.3	-0.8	8.7	+0.5
8	9.9	+0.6	8.0	-0.7
10	10.1	+0.2	8.0	0.0
24	9.5	-0.6	7.6	-0.4
Overall Population Change		+1.8		-0.5

The population continued to increase gradually in Unit 2 for periods up to 10 hours after sludge addition, but the population of Unit 1 was observed to be declining after 6 hours. This decreasing population suggested that some factor in Unit 1 had become limiting for bacterial growth. It is believed that food was not the limiting factor as the averagle volatile solids content added to Unit 1 was 5400 ppm greater than for Unit 2. Initially, there were nearly twice as many bacteria, 10.3 compared to 5.9 million/ml, present in Unit 2 as there were in Unit 1. If food material was the limiting factor why would a larger population with less food available continue to increase while a smaller population provided with more food experienced a decline? It is possible that a larger concentration of organic matter could stimulate an increase in bacterial numbers which would deplete the oxygen content to negligible levels (Table 5). Once the DO was exhausted, further population increases would be retarded even though substantial amounts of food materials remained. In as much as the biological oxygen demand is a response of the organisms to the organic matter in the added raw sludge, it appears most logical that the limiting factor would be that of dissolved oxygen.

When sterilized raw sludge was used the number of bacteria was also observed to have increased after 2 hours, but to a lesser degree. In fact, greater increases for Unit 1 and Unit 2 were realized at the 4- and 5-hour intervals (Tables 6 and 7). This observed latent population increase and accompanying biological oxygen demand is the exclusive response of the activated sludge organisms to sludge addition. It will be noted from these tables that the population increases were largest for Unit 1. This population increase would have a substantially greater oxygen requirement. The smaller additions of sterilized raw sludge added to Unit 2 effected more gradual changes in bacterial population. In this case, the smaller

food supply was probably the initial limiting factor. It is apparent from these studies that the immediate initial large increase in population was largely due to the bacteria present in unsterilized raw sludge. When adding sterile raw sludge, the largest increase in bacterial population occurred 2-4 hours after addition. Tables 3 and 4 provide information which differentiates the biological oxygen demand. Approximately one-half of the DO value reported in Table 3 can be attributed to organisms present in the raw sludge. Tables 3 and 5 provide a comparison between the shock loading effects of 100 ml and 400 ml additions of unsterilized raw sludge.

Reduction of volatile solids was also observed to be more efficient when smaller volumes of raw sludge were added. The volatile solids reduction for Unit 1 was consistently lower than that for Unit 2 (Tables 9 and 10). These large differences in efficiency narrowed considerably by the 8th day. The final overall reduction at the termination of the 12-day comparison period was 5% greater for Unit 2. Large additions of raw sludge lengthen the maturing phase of the system by depleting the DO concentration to negligible levels. It has been reported that this condition retards the necessary development of floc formation without which a suitable removal of organic material cannot be attained (Wuhrmann, 1964).

Table 9. Reduction in Volatile Solids

Batch Unit Number[1]	Total Days of Operation	Volatile Solids Reduction by Time Period			
		Day 5	Day 12	Day 22	Day 26
1	22	40.8	53.6	65.0	-
2	12	50.5	58.6	-	-
3	26	13.3	16.9	25.8	26.4

1-Batch unit numbers; 1 - 400 mls sludge added in a single addition

2 - 400 mls sludge in 100 ml portions

3 - 400 mls sludge added in 100 ml portions

Table 10. Percent Reduction of Volatile Solids

Day	Unit 1[1]	Unit 2[2]	Unit 3[1]
0	21.2	27.7	4.7
1	14.9	32.3	4.4
2	20.5	38.1	6.4
3	30.3	49.3	9.3
4	39.9	53.6	11.7
5	40.8	50.5	13.3
6	38.6	50.1	12.4
7	44.9	48.9	14.6
8	49.8	48.6	13.8
9	52.2	52.5	15.9
10	52.9	56.6	18.1
11	53.4	58.9	17.5
12	53.6	58.6	16.9

1 - Units 1 and 3; 400 mls sludge added in a single addition

2 - Unit 2; 400 mls sludge added in four separate 100 ml portions

The effect of low temperature (10°C) on the aerobic digestion process was apparent from the investigations conducted on Unit 3. There was an initial population increase resulting from the addition of unsterilized raw sludge to Unit 3. However, this increase was not followed by any subsequent population gains (Table 8). Instead, the total number of bacteria remained relatively constant. The low temperature apparently inhibited a population expansion of the activated sludge organisms. Therefore, the increase was attributed primarily to the organisms in the raw sludge added. Once incorporated into the contents of batch Unit 3 and provided with oxygen, these organisms apparently did not find temperature conditions suitable for rapid growth.

The addition of sterile raw sludge to Unit 3 did not effect a large population increase. The initial large increase in bacterial numbers, reported two hours following addition of unsterilized raw sludge, was conspicuous only by its absence. It appears evident that this initial increase in total population is due to organisms added with the raw sludge and is not a response of the activated sludge organisms. Also, the limitations imposed by low temperature on bacterial activity was illustrated by an almost static population. Variations in the total bacterial counts observed are probably due to inherent weaknesses of the standard plate count method.

The rate of population increase for Unit 3 was less than that of Units 1 and 2 (Table 2). It appears that there is a fraction of the total bacterial population (psychrophiles) in the raw sludge which can function to some extent at sustained low temperatures. The observed gradual

increase in bacterial numbers of the activated sludge is probably due to this group. The slower growth rate and the consistently higher DO concentration (Table 1) indicates less bacterial activity for Unit 3.

In terms of the actual number of bacteria present, the total population on day 26 for Unit 3 was 10.5 million per ml. The overall reduction in volatile solids for the same period was 26.4% (Table 9). Table 2, shows that the population on day 12 for Unit 1 was between 9.8 and 11.7 million/ml with a reduction in volatile solids of 53.6% (Table 9). Hence, it is obvious that sheer numbers of organisms do not guarantee any specific reduction value. More important are the limiting physical conditions of the environment, such as temperature and dissolved oxygen. From the data obtained, it did not appear as though rate of aeration was a limiting factor in the performance of the various batch units. It is well known, however, that all bacterial types demonstrate some optimum temperature for metabolic activity. As the temperature drops, different bacterial forms become dominant within the population. Likewise the nutritive requirement of these organisms will differ. It is not known which bacterial species were dominant at $10^{o}C$, but it was determined that their efficiency in terms of volatile solids reduction was significantly less (Table 9).

The low temperature study (Unit 3) supports two contentions; 1) the rapid initial increase in population is primarily due to the organisms added with the raw sludge and 2) that a low temperature (10^{o}) severely retards bacterial activity. It is postulated that given a suitable temperature of operation, the next controlling factor in process efficiency is the dissolved oxygen concentration. It is likely that shock loading retards the development of floc particles by effecting an oxygen deficiency. This results in a considerably less efficient system.

In conclusion the in-laboratory studies have shown;

1. Much of the immediate oxygen demand following addition of sludge to the units was due to microorganisms present in the sludge added.

2. Low temperatures for extended periods of time greatly decreases the efficiency of an extended aeration process.

3. Method of sludge addition greatly influences process efficiency. Smaller, more frequent additions of raw sludge to the digester lead to greater reductions of volatile solids than do larger, less frequent additions.

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GLOSSARY

Activated Sludge Organisms - microorganisms present in the mixed liquor in the digester, as opposed to those added in any given sludge addition.

Biological Oxygen Requirements - oxygen demand exerted to meet respiration requirements of microorganisms in mixed liquor (not the same as biochemical oxygen demand).

Dissolved Oxygen Residual - minimum quantity of dissolved oxygen present in batch unit following sludge addition.

Maturation Phase - refers to the period of time, following a sludge wasting event, necessary to build solids content and bacterial populations to levels required for efficient operation.